PROCEEDINGS

AN INTERNATIONAL WORKSHOP ON QUALITY IN UNDERWATER WELDING OF MARINE STRUCTURES

Sponsored by:
The Offshore Minerals Management Service
The Colorado School of Mines—Center for Welding Research
The National Bureau of Standards

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I. EXECUTIVE SUMMARY

Clearly, this workshop has established the existence of a need for, and a strong interest in, improving the quality of underwater welds. That need extends internationally and includes structures and pipelines, as well as floating systems. The workshop has also challenged us as intelligent beings to think of the future in a new light. The problems experienced with underwater welds, are the opportunities of the future researchers and developers.

The opportunities extend across many fields and in most cases offer the added challenge of being multi-disciplinary. Materials technology, from different strength, but more weldable, base metals to new welding consumables will be needed. New equipment designed to withstand greater depths as well as taking advantage of the latest electronic and computer technology. But perhaps the most exciting of all is the concept of autonomous intelligent robot systems capable of both inspection and welding. There will be many technological achievements between now and the time of these robots. But, certainly, they will exist and the vision of internationally recognized individuals of the advancements yet to happen, will surely drive those changes. The participants in this workshop have completed their tasks -- it is now left for us to respond with our best ideas and most fruitful efforts. The quality of underwater welding will then move toward excellence.

The organizing committee for this workshop extends a special thanks to the participants. Everyone who attended made contribution and the result was a compilation of the cummulative ideas of the world's experts in underwater welding.

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II. INTRODUCTION

2.1 BACKGROUND

Replacement of a tubular member in a structure or repair of a fracture in a pipeline may both seem like fairly mundane subjects and certainly not worthy of an international workshop to discuss the issues surrounding those topics, but when that repair or replacement takes place at a depth of 500 feet, or even 100 feet, below the surface of the ocean or by an autonomous robotic vehicle inside a flooded nuclear reactor building, the welding in these activities takes on an added dimension of complexity and difficulty. Not that many years ago, the United States began, along with many other countries in the world, to explore for oil offshore. The initial drilling and production platforms were generally small and in shallow water. Many of those platforms were small enough that when they reached the end of their useful lifetime and began to experience failures due to fatigue, corrosion, stress corrosion cracking, and other causes, they were simply abandoned. Some were perhaps salvaged for the scrap material in them, and no thought of repair was ever made.

The Navys of the world have always had the potential problem for damage below the waterline of their vessels and while, for the most part, a vessel can travel to a dry dock and be repaired permanently at a later time, there is some criticality to making a proper temporary repair below the waterline of a damaged vessel. As the materials used to build ships increase in strength and performance, that repair welding becomes more and more critical and if done improperly could potentially cause more serious damage than the repair was intended to fix. So as the difficulty of repair of vessels underwater increases and as the search for oil drives many of the countries of the earth into deeper and deeper water where the cost of the platforms increases dramatically, the need to repair those structures becomes increasingly a design criteria rather than an afterthought associated with the discovery of a failure.

Underwater welding is becoming one of the major research and technology transfer issues for the next decade. The principal need, as recognized by the organizing committee of the workshop, is for better underwater welds; and while better may mean a number of different things from better metallurgy to better consumables to better mechanical design to better quality assurance in nondestructive testing, the issue at hand is quality. Hence, the name of this workshop, "Quality in Underwater Welding of Marine Structures". Just as the oceans of this world connect all of its major continents, underwater welding is also a universal issue which could not be adequately discussed in any but an international forum.

2.2 WORKSHOP ORGANIZATION

The workshop organizing committee, after much discussion, determined that there were three primary topic areas which were of importance in the quality of underwater welds. Those three topic areas were (1) the welding itself; (2) any inspection which was required to determine the degree of repair needed and

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the adequacy of the welding which took place; and (3) the impact of the advanced technologies which are currently being developed and which will be applied in underwater welding during the next few years. Since there is a significant difference between shallow underwater welding and deep underwater welding, the three primary topic areas were finally divided into four separate workshop task groups as follows:

1. Shallow Underwater Welding (less than 300 feet in depth)
2. Deep Underwater Welding (greater than 300 feet in depth)
3. Inspection
4. Advanced Technology

The workshop was organized so that on the morning of the first day there were two keynote speakers each addressing a general subject of interest to the workshop and four white papers delivered, one from each of the session chairmen. The white papers were designed as working documents which set the tone for the session discussions. Beginning on the afternoon of the first day, the sessions met together to outline the state-of-the-art and research objectives for their topic area during the next several years. Session chairmen led the discussion and session co-chairmen took close notes which were then transcribed during the evening of the first day into typewritten draft format. On the morning of the second day, each of the sessions once again met to discuss their draft format documents and make revisions. Finally, at the end of the workshop, each of the session chairmen presented the outcome of their sessions for comment and suggestions from the workshop attendance as a whole.

This workshop proceeding was then assembled to include each of the white papers and the two keynote addresses along with the final documents prepared by each of the working sessions. While the 1-1/2-day format of the workshop necessitated a compressed scheduling, the workshop was organized in such a fashion that all of the participants got together informally, both at lunch and at a reception on the evening of the first day to allow for additional discussion in preparation for revision and additional comments to the working session reports. In addition the compressed time schedule of the workshop allowed a great number of busy and internationally recognized individuals in the field of underwater welding to attend the workshop without excessive demands on their time.

2.3 WORKSHOP OVERVIEW

Each of the individual session reports contained a list, in order of importance of the subject areas which were discussed. It is not the intention of this overview to reiterate the findings of the various sessions but instead to present some of the flavor or essence of the workshop which resulted from much of the discussion and which may not have been reported in the individual session documents.

The large number of international participants provided confirmation that underwater welding is an important subject of interest, almost universally throughout the world, and is a subject area that will continue to increase in its importance in the international welding community in the next few years.

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Another item noted by many of the participants at the workshop was that both welding consumables and welding equipment which are used for underwater welding are often simply adaptations of existing conventional welding apparatus and supplies rather than being designed specifically for the application at hand. As research continues into the specific characteristics of the environment, underwater welding equipment and consumables need to be designed and developed to take advantage of those characteristics. As new applications for underwater welding develop the market will expand accordingly, and may represent a considerable market requiring specific research and development.

Although differing somewhat in character, the workshop participants noted that temporary repair of vessels and maintenance welding of offshore structures have many similar attributes. For that reason, the workshop sought to bring together people who have been involved in each of these fields. The discussions which ensued often lead to both agreement and discovery of important information by people in each area. Thus, it should be concluded that future activities in underwater welding should include participants from the two subject areas: floating and fixed structures.

One area of greatest overlap between the repair and maintenance of floating and fixed structures is in the application of advanced technology. Remote robot inspection and repair activities will be applied to underwater welding as research progresses in the area of artificial intelligence, sensor technology, computer vision technology, and inspection. In the underwater environment, many standard sensors cannot be applied. Transmission of energy is distorted. For example, light energy experiences rapid attenuation, while acoustic energy has increased transmittal characteristics. Thus, development of intelligent robot systems that possess the capabilities of vision, telepresence, and self-actualization will certainly be different for underwater activities than for above-water systems.

Due to the inherent difficulties and risks of human participation in the welding and inspection process underwater, much technological development should be applied toward the goal of reducing the need for human presence. Research and development priorities for underwater welding and inspection will probably be toward intelligent and autonomous robot systems. Since the underwater environment is unique, the equipment, consumables, and power supplies that are developed will necessarily be different. Consequently, the underwater welding and inspection community may not be able to depend upon the technologies of others but will need to be directly involved in research and development for underwater application of advanced technology.

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III.   FIRST KEYNOTE ADDRESS – H.C. COTTON

"Underwater Welding – State-Of-The-Art"

Abstract

(Prepared by: J.E. Jones)

Underwater welding is performed for a wide variety of reasons and under a diversity of conditions worldwide. The need for clear understanding of processes, procedures, and methodologies has never been as great before. The current state-of-the-art of the practice of underwater welding can be described as both advanced, as well as rudimentary. High technology is being applied in many specialized applications while ordinary welding is often done manually under less than ideal conditions.

Currently, the United States performs much wet underwater welding. Much of the remainder of the world uses enclosures for this activity. The enclosures are typically of two types. The one atmosphere enclosure acts as a negative pressure vessel to withold the tremendous pressure of the depths of sea water. Other enclosures use a thin shell, which is maintained at a slight (approximately 4 in. of water) over pressure to minimize leakage and maintain a dry environment. The differential pressure chamber is preferred for complicated joints which are difficult and expensive to fit with a one atmosphere chamber.

As depth increases, the pressure in a differential pressure chamber must be increased dramatically and the density of shield gases is a function of pressure. As the pressure increases, the density of the shield increases, finally becoming too dense to allow observation using fiber optic systems. Thus, imaging techniques which would allow elimination of the human operator from the hazardous environment become difficult, or impossible.

A variety of shielding gases are used in underwater welding applications. Due to the interaction of accumulated shield gases with the environment in a chamber, the choice of gas, if used extensively, is important. Nitrogen is a possible choice of shield gas component. However, nitrogen has been shown to cause notch toughness problems in higher strength steel underwater welds.

Hydrogen is constantly available in the underwater welding environment. Much work has been completed to study the hydrogen behavior in underwater welds. It is interesting that data shows the electrode polarity to have a significant influence on the hydrogen content of underwater welds. As the pressure increases, welds produced with electrode positive current will show a steady parabolic rise in hydrogen content which begins to level off at just greater than 200 feet at around 10 ppm. However, welds made with electrode negative polarity show a slight increase to above 10 ppm as depth increases to 100 feet then a rapid drop off of hydrogen content occurs, leveling off below 5 ppm for depths of 200 feet and greater.

This information represents only a small fraction of recent results of underwater welding study. This workshop is designed to present a great deal of information and to examine that information in the context of future directions for study. The workshop will certainly fulfill the expectations because of the diversity and collective expertise of the participant.

IV.   SECOND KEYNOTE ADDRESS

Future Needs - Prevention and Repair of Underwater Damage to
Marine Structures

C. E. GRUBBS

4.1   INTRODUCTION

As the number of offshore structures
increases and the aging existing structures
are subjected to more fatigue, corrosion
and accidental damage, there is a dramatic
increase in the need to (1) plan offshore
operations, including the installation of
new structures, so as to minimize the
possibilities of accidental damage and (2)
be prepared to repair underwater damage
when it does occur. The later includes
research and development to optimize
properties of underwater welds and,
after properties are determined,
engineering studies and mock-up testing
to determine optimum repair designs and
techniques.

It is hoped that this paper will be of
interest, and perhaps even provide some
useful information to those involved in
the design, installation and underwater
repairs of offshore structures. Opinions expressed are based on over fifteen
years of personal experience in underwater welding research and development
and participation in hundreds of underwater welded repairs to offshore
structures.

Before examining our needs, let's take a brief look at things related to
underwater damage and repairs.

4.2   CAUSES AND TYPES OF UNDERWATER DAMAGE (EXAMPLES)
4.2.1   Design Errors

A large deep water structure was launched from a barge and as it was
being submerged it suddenly plunged to the seabed when buoyancy chambers
imploded because stiffener rings were spaced too far apart.

Conductor guide panel welds are failing in U.S. waters and the North
Sea. The fatigue failures result from out-of-plane bending of the conductor
guide panels. Causes of excessive bending can be attributed to the fact that
many conductor guide panels result in excessive resistance to the cyclical
vertical movement of the water. If an "Opaque" conductor guide panel is
installed at an inadequate water depth and failure of the welds that connect
it to the structs and legs of the structure can be guaranteed. Inadequate
wall thickness of struts and noded sections will hasten the failures.

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4.2.2 Unanticipated Loads

The bottom ends of four of eight legs on a large offshore structure were temporarily capped to provide additional buoyancy during the submerging of the structure in deep water. The 52"ϕ x 1/2" wall legs were not designed for the external pressure encountered and consequently imploded.

4.2.3 Accidents

The inadvertent release of heavy objects such as pile and conductor sections continues to wreck havoc on offshore structures. These accidents are most likely to happen during installation of structures but also occur during installation and replacement of boat landings and fendering systems.

Many structures have been damaged during installation of skirt piles. The damage frequently occurs when skirt piles are being guided or "stabbed" into the first level of bell-guides below water without adequate visual observation (video or diver) of the orientation of the pile end and the bell-guide.

4.2.4 Collisions

As the number of offshore structures increases, so grows the fleet of vessels that service the offshore industry. With the increased traffic, day and night, the risk of collision damage to the structures increases. Perhaps the accumulated damage by crew and supply boats colliding, however "gently", with boat landings, structures members and risers causes more damage than collisions that make the headlines.

4.2.5 Corrosion

Damage from underwater corrosion can be dramatic and sometimes bizarre. This writer was involved in the repair of a structure that had over six thousand holes in tubular members. And, loss of weld metal and "knife-edge" corrosion in the heat-affected zones, where struts and braces connected to legs, was so extensive that from the splash zone down to about 150', over half of the welded joints had to be repaired.

The damage described above was typical on six structures. None had been in service longer than five and a half years. Cause of the corrosion was probably (1) improper grounding of barge mounted welding machines used to weld on the structure during installation of decks, piping, etc. and (2) intermittent use of the impressed current cathodic protection system.

4.2.6 Fatigue

Starting in 1974 we have observed a trend of an increasing frequency of fatigue failures in welded tubular joints of offshore structures. The failures start as cracks in the heat-affected zone at the toe of groove and

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fillet welds and then propagate through the wall of the tubular members and around the perimeter of the welded joints. As the cracks propogate along the heat affected zones they frequently branch out several inches into the wall of the member. With few exceptions, the cracking occurs in the wall of the larger diameter member. Where conductor guide panels have been located at depths too shallow for the sea states they encounter, fatigue failures have occurred in less than two years. Other fatigue failures, especially where struts and braces weld to legs, have occurred and will continue as the older structures approach the end of their fatigue lives. Which, may have been shortened by Hurricane Juan's meandering visit to the Gulf of Mexico.

4.2.7 Prevention of Damage

A study of case histories of underwater damage to offshore structures clearly indicates that most of the damage could have been prevented. It is not the purpose of this paper to address the prevention of damage caused by design errors, unanticipated loads, corrosion nor fatigue, however; the prevention of accidental damage (other than collision) will be discussed later as one of the "future needs".

4.2.8 Inspection of Underwater Damage

The importance of an accurate comprehensive inspection report cannot be over emphasized. The first underwater inspections may be made merely to determine the approximate severity and extent of damage. However, in planning the final inspections, one must keep in mind that the information reported may be used as the basis for, (1) determining the exact extent of the repairs, (2) engineering design of repairs, (3) procurement of materials, (4) fabrication of repair sections, (5) project planning, scheduling and management and (6) the inspection report may be used by contractors for estimating time and cost.

Historically, inspections of underwater damage to offshore structures fail miserably in reporting the full extent of damage. One of the most common and costly errors is inaccurate reporting of the extent of circumferential and linear deformation of members. The deformation is most often found to be greater than reported.

4.2.9 Preparation for Repair of Damage

Preparation for underwater repair – and prevention – of damage should proceed with the design and selection of material for new offshore structures. To disrupt drilling and production schedules to qualify welding procedures and design repairs results in a great and unnecessary loss of time and money. Preparation for underwater repairs will be discussed later as one of our "future needs".

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4.2.10 Specification for Underwater Welding (ANSI/AWS D3.6)

Professor Harry C. Cotton has succiently stated "there is no reason to suppose that welds made underwater, whether made in a wet or dry environment, are in any way exonerated from compliance with those vital parameters which control welding in air at one atmospheric pressure".

For that reason, and because underwater welding has essential variables not encountered in welding above water, the above underlined specification was developed by the American Welding Society. The committee that developed the specification was selected and started work in 1974. The specification was completed and published by AWS in 1983. The specification was developed in response to the needs of the offshore industry and is designed to make it possible for a user of underwater welding to conveniently specify and obtain underwater welding of a predictable performance level. The specification is suitable for application to various types of underwater welding including wet, dry hyperbaric and one atmosphere.

4.2.11 Wet/Dry Hyperbaric and One-Atmosphere Welding

A great number of scholarly, and some practical, papers have been written about underwater welding. The following observations are based on my personal experience and observations of work done by others.

Wet welding is certainly the most controversial. However, on the positive side, since 1971 hundreds of underwater wet welded repairs have been made without any reported failures. And, wet welding is in most cases the least costly and in some situations is the only method that can be used. On the negative side, wet welds are less ductile, have more porosity (which increases with depth) and, depending on the chemistry of the metal being welded, can produce extremely hard heat-affected zones. In spite of this, recent tests indicate that good wet welds have crack resistance properties that compare favorable with dry hyperbaric welds and welds made above water.

It is well known that wet welding is "depth sensitive". The maximum water depth at which acceptable wet welds can be made is not yet known. (Global Divers and Contractors, Inc. qualified wet welding procedures and welders down to an unprecendented depth of 390' in accordance with ANSI/AWS D3.6 Type B in June 1985.)

4.2.12 Quality Assurance of Underwater Welds

It is essential that any project plan for underwater welded repairs include specific plans, equipment and personnel to assure that the work is done in conformance with the engineering design and governing welding specifications.

Methods and devices suitable for inspection and non-destructive examination of underwater welds include photography, television, radiography, magnetic particle, weld size gauges, ultrasonic flaw detectors and visual examination by the underwater welding inspector.

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The ANSI/AWS "Specification for Underwater Welding" D3.6 has sections that cover underwater quality assurance in detail.

4.2.13 Future Needs

The offshore industry, including those who produce, transport and market petroleum products, and the service companies, desperately need a better return on their capital investment and general operating expenditures. Not in recent history has crude oil sold for so little per barrel nor service companies and workers been compensated so little for their labor and risks. The diving industry has been particularly hard hit. Competitive pricing for day rate and fixed price projects leaves little or no profits for the larger companies and in some cases pending bankruptcy for the small companies. Divers, especially welder/divers, are earning less than they did ten or twelve years ago.

In the 1970's there was a great deal of productive research and developmental work done to extend the depths at which man could work effectively. New breathing gases were formulated and tested, one atmosphere "diving suits", small submersibles (some with diver-lock-out capabilities) and remotely operated vehicles were developed. Dry hyperbaric welding procedures were qualified down to 1,000' and contracts were awarded to develop mechanical methods of repairing pipelines at depths greater than 1,000'. And, wet welding research and development resulted in a new and viable method for repair of underwater damage on offshore structures.

The funds for the aforementioned developments - so vital to the offshore industry - came from oil and gas companies and from contracting companies that were making a profit. Unfortunately, much of funding for research and development of things that go underwater has virtually dried up. So, money must be spent where it will produce the best possible return on investment.

This paper addresses two future needs. One will cost very little and the other will cost less to do now than if we wait until an emergency underwater repair is needed and we have no repair plan or qualified welding procedure.

FUTURE NEED NO. 1 is the prevention, or at least the significant reduction of accidental underwater damage to offshore structures. A study of case histories will undoubtedly show that most, if not all, of the accidents could have been prevented. Contributing factors to the types of accidents we are discussing usually includes one or more of the following:

(1) Lack of planning and failures to anticipate problems.
(2) Errors in human judgment or maybe no judgment at all.
(3) Lack of experience and failure to follow instructions.
(4) Improper selection or use of equipment (especially lifting and rigging equipment) and failure to test and/or inspect that equipment,
(5) Lack of communications. The best laid plans are nothing but good intentions unless everyone involved knows what he is supposed to do.

My suggestions for reducing accidents that cause underwater damage to offshore structures is to establish a committee of six to eight members.

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Prime requirement for qualification for membership would be a lot of experience in the installation, operation and maintenance of offshore structures. I know the type of man I am talking about. Some have better qualifications than others because "accidents have happened on their shift". All can make constructive contributions to preventions of accidents. None are good at "paper work". So, assign an engineer as secretary to the committee. He must have offshore experience and be a good "listener".

The committee would discuss the various types of accidents that have occurred-some of them repeatedly – and develop plans to prevent the accidents from re-occurring. End product of the committee would be an illustrated accident prevention manual with a safety check-list for the various offshore tasks that have resulted in accidental underwater damage.

The results of the committee's work would be distributed on a need-to-know basis, especially to those with comparatively less experience than those on the committee.

FUTURE NEED NO. 2: For welds made above water, essential variables and properties are well known. And, if welding procedures need to be developed and qualified for welding new materials, such as controlled rolled micro alloyed steels, the task is simple and takes little time compared to qualifying a new welding procedure underwater, especially at unprecedented depths.

For dry hyperbaric welds, properties are well known down to about 350' and are reproducible to about 650' with a greater degree of difficulty. Very few companies have qualified dry hyperbaric welding to 650' or even 350'.

Until recently there was little interest in specifying wet welding for repairs deeper than about 150'. Then, at least three things caused a dramatic change in the interest in – and specification of – wet welding for repair at greater depths.

1. Publication of the ANSI/AWS D3.6 "Specification for Underwater Welding" made it possible for the users of underwater welding to conveniently specify and obtain underwater welding, wet or dry hyperbaric, of a predictable performance level.

2. Colorado School of Mines and others released reports that indicated properties of wet welds compared more favorably with dry hyperbaric welds and welds made above water than had been previously thought. In fact, wet welds tested had better crack resistance properties at low to moderate stress levels than welds made in air.

3. A major oil company had need to make welded repairs on an offshore structure down to 320' because of the configuration of the damaged areas, wet welding was the only viable solution. Welding procedures and welders (fillet welds on pipe and groove welds on plate) were qualified at –325'. The offshore repairs were completed ahead of schedule. Properties of the welds made at the underwater work site were significantly better than those of welds qualified in fresh water in the wet-pot on shore.

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A valuable lesson should be learned from item (3) above. The oil company prepared bid specifications and met with five selected diving companies late in January 1985. One at a time, three of the diving companies prepared their hyperbaric facilities and attempted to qualify wet welding procedures at the unprecedented depth. The required welding procedures, and welders, were not successfully qualified until June 1985. Meantime, drilling and production schedules were disrupted at virtually incalculable costs. Much of the lost time could have been avoided if welding procedures had been qualified prior to installation at the structure.

That brings us to our No. 2 future need. A great deal of time and money would be saved in the future if steps were taken now to avoid similar situations. The objective would be to determine the properties of wet welds at various depth and on various materials, and develop optimum repair methods for typical types of damage that may occur.

The program would include:

1. A determination of needs of the offshore industry including testing requirements.

2. Selection of comprehensive testing facilities.

3. Procurement of pipe and plate material with the proper predetermined chemistry.

4. Preparation of hyperbaric welding facility so as to provide optimum visual observation of welding by the customers and their representatives.

5. On-site examination facilities for ultrasonic, magnetic particle, radiography, root and side bends, tensile and macroetching.

6. Selection of certified welder/divers. Minimum of four welder/divers would be used so work could proceed on a 24 hr/day basis. And, so the evaluation of weld properties would not be based on the skill (certainly an essential variable) of only one or two welder/divers.

7. Making welds on various materials and at various depths and testing to determine properties to be used in designing repairs.

8. Weld mock-ups using different repair designs and testing the welded mock-ups to destruction.

9. Development of contingency repair plans for types of damage that is most likely to occur.

DISCUSSION OF FUTURE NEED NO. 2: One might ask why does the work described above need to be done when wet welding procedures have already been qualified down to 390' (weld was qualified at 325' and, per ANSI/AWS D3.6, is qualified to 390'). During attempts to qualify the subject welding procedures, there was a great sense of urgency to complete the qualifications and mobilize for the offshore repair.

Consequently, when problems were encountered, there was not enough time to methodically eliminate variables one at a time to determine which variable – or variables – caused the problem. For example, in the initial phase of the welding, root bead cracking was encountered. The problem was promptly eliminated by changing (1) welding electrodes, (2) plate on which welds were being made, (3) backing bar, (4) joint detail and (5) degree of restraint on weldment. Under research and development conditions the specific cause of the cracking can be identified and avoided in the future.

V.A. DEEP UNDERWATER WELDING WHITE PAPER
N. Christensen/H. Hoffmeister

Underwater welding in deep waters has
been and will be an important key to the
exploitation of offshore gas - and oil
fields. The items considered by session
II have been grouped as follows:

1.   Range of depth of underwater
      welding and corresponding
      welding processes.

2.   Materials to be welded and
      quality requirements to be
      applied to the joints.

These topics have been discussed under
the aspects of present state of the art,
current R&D projects, future research needs.

5.1 THE RANGE OF DEPTH AND CORRESPONDING
WELDING PROCESSES

Successful tie-in operations at 150m depth have been reported for North
Sea installations, using covered electrodes. Subsequent work including fjord
testing indicates that a reasonable weld joint quality can be achieved at
considerably greater depth, using stick electrodes for a combination of this
method with gas-shielded root pass welding.

Opinions differ as to the depth beyond which metallurgical problems will
become significant. Reduced weld toughness would be expected due to an
increased absorption of carbon and oxygen with increasing pressure from the
shielding atmosphere, which essentially consists of carbon monoxide its
partial pressure determining the concentration product %C X %O.

Hydrogen-induced cracking may arise from moisture present in electrode
coatings and from infiltration of humid habitat gases into the arc
atmosphere. The latter type of hydrogen contamination is common to all
welding processes including inert-gas shielded methods. Infiltration of
surrounding gases is intensified by arc constriction under increased
pressure. This is not merely a result of isostatic compression, which in
itself imposes a handicap on covered electrodes producing a constant mass of
shielding gas per unit mass of deposit. The effect is observed also with
inert-gas shielded processes when the mass flow is increased in proportion to
the pressure while arc constriction becomes appreciable at 100 to 150m depth
and is fully developed at about 300m. However, it has been shown that arc
atmosphere contamination by chamber gas depends on shielding gas flow rates,
and that optimum flow rates have to be established for sufficient arc
protection. The minimum of contamination corresponding to an optimum of flow
rate is seen to increase with pressure.

On this background it would seem reasonable to restrict deep water welding to depths greater than about 150m, since at smaller depth the problems can be overcome even in manual metal-arc welding. An upper limit is suggested at 500m depth. There are clear indications of a need for reliable welding procedures at 350 to 400m depth, both for purposes of repair and tie-in operations. Simulated testing has revealed that inert-gas shielded processes will work in a satisfactory manner up to 50 bar pressure or about 500m depth. On the other hand the safety and the efficiency of the welder would indicate a more conservative depth limit than the physics and metallurgy of the welding process. It is a fair assumption that mechanized remotely controlled welding will replace the human operator in future welding at great depth. Meanwhile, manual welding must be resorted to.

Since a limited depth has been indicated for welding with covered electrodes, and on addition this process is not suitable for mechanization, it is concluded that future efforts should concentrate upon <u>continuous processes</u>, stick electrodes being considered only with regard to proper range of application.

Of the inert-gas shielded processes, GTAW and plasma-arc have the advantage of a separate choice of welding parameters and filler wire addition. Electrode wear and electrode contamination by spatter or by accidental contact with work-piece or wire however are a worthwhile consideration, both factors being known to reduce the arc stability. On the basis of general principles the plasma-arc process would seem advantageous, since there is no risk of short circuiting and less danger of contamination of spatter. The ease of operation and ruggedness of plasma-arc guns will certainly also be factors of importance, but at present, no technical application is known.

Arc stability, proper weld metal droplet transfer, and adequate penetration are requirements that have not been easy to meet in past experience with high-pressure GMA welding. Both requirements are strongly dependent on the operational conditions including the choice of shielding gas, and on the characteristics of the power source. These characteristics, e.g., the use of pulsed current, will of course also be important in GTA and PA welding.

Flux-cored arc welding should be considered as a separate method distinct from solid wire GMA welding. FCAW has the advantage of a good arc stability, which has to be weighed against the risk of slag entrapment sometimes reported as an objection against this method. At any rate the slag must be removed, which may not be an easy operation in narrow grooves. At this point it might be appropriate to look for slag-protected consumables properly adjusted for use under hyperbaric conditions.

5.1.1 Summary

Mechanization, perhaps automation, of pipe butt welding is essential at up to 500m sea depth, the deepest identifiable need. Such automatic welding is desirable at lesser depths even where manual welding is practicable because of the quality of the welds and the potential for speed. Manual intervention will be required to a greater or less extent.

The GMA, GTA and possibly Plasma welding processes appear to be the most suitable for such automatic welding. The plasma process is yet to be developed. Working experiments using GTAW and GMAW exist but these require futher development and deserve funding.

The SMA process works reasonably well down to about 170m but becomes increasingly inefficient and difficult to use with increased depth. The performance of SMA welding could possibly be improved by development of the flux coating but is doubted if such action would be worthwile.

At depths deeper than 500m fusion welding may not be attractive but alternative diffusion bonding processes are interesting and may soon find application in such areas as sub sea completions. Depth probabilities may soon exceed 750m. Diffusion bonding processes are less susceptible to depth effects and can be automated. Friction, explosion bonding are examples of appropriate processes.

The choice of alternatives for future developments has been influenced by the present opinion with respect to the ability for the diving individual to perform at hyperbaric pressure.

5.2 TYPES OF MATERIALS AND REQUIREMENTS

The types of steels to be welded include a wide range of chemical composition, depending on the methods used to obtain the required strength. There is a clear trend towards steel of a carbon content well below the conventional level of about 0.20 %C.

Welding conditions for low-carbon, medium-strength steel should of course be chosen so as to avoid reduced toughness in the HAZ. This task, however, is common to welding of such steels in general, and should therefore not require any special attention for applications in underwater welding. In general, less rigorous routines of preheating, interpass temperatures and postheating may be expected.

The most important feature of low-carbon steels is clearly the reduced risk of hydrogen-induced cracking. This applies to cracking of the HAZ (under-bead cracking) as well as to hydrogen fissures in the weld metal. A beneficial effect of low carbon steels could also be a better notch toughness of the root pass due to a reduced carbon pickup from the parent plate. It is not known whether the concentration product (%C) (%O) referred to earlier for covered electrodes will be affected by the level of parent plate carbon; for inert-gas shielded processes and low initial carbon content would clearly be desirable.

It is important that quality requirements to underwater welded should in principle be equal to those specified for welding in open air. It may nevertheless be useful to investigate aspects of quality that are known to be affected by pressure and humidity.

Considering first the risk of HAZ cracking, it is well known that covered electrodes now available will give reproducible hydrogen levels H_{DM} down to

2-3 ml H_2 per 100g deposit, or H_{FM} about 1.5 ppm on a fused-metal basis. Values well below this level are readily obtained with inert-gas shielded processes. In underwater welding, infiltration of humid gases from the environment may easily raise the absorption of hydrogen to a level comparable to that considered normal 10 or 20 years ago. A qualification procedure for deep water welding should therefore include evidence of absence of cracking at a fairly high hydrogen level.

Similarly, hydrogen micro-fissures in the weld metal have been considered a matter of historical interest up to recent years. They may be back again in hyperbaric weld due to an increased hydrogen level. A similar type of weld metal defect has lately received considerable attention under a new label of "chevron cracking". So far they have been observed in submerged-arc deposits of a yield strength higher than about 500 MPa, at hydrogen levels H_{FM} higher than about 2 ppm.

A quality criterion often included in specifications of acceptancies is the peak hardness, measured in procedure testing in the HAZ of the cap layer and sometimes also close to the root. Peak hardness is clearly related to the composition of the steel, mainly to the carbon content. It would in particular be useful to clarify the intentions of maximum hardness requirements: whether they are considered as an indication of safety against embrittlement and cracking in general, or as a precaution media (stress corrosion cracking). In the former case permissible hardness levels should be adjusted according to the type of steel used, higher levels being acceptable in conventional medium carbon steels than in low-carbon grades. In the latter case hardness limits of, say 260 Vickers units would seem over-conservative in the absence of a corrosive environment.

5.2.1 Summary

Due to conventional compositions of existing structures, welding procedures used to be found to deal with high carbon equivalents. New constructions should be designed and be made of materials such as to simplify hyperbaric repair or modification which might be required. How far a reduction in carbon equivalents, for example, might be helpful in this connection is uncertain. Hardenability is also important and the two criteria may conflict. The effect of such limitations upon the properties of hyperbaric welds made by different processes may not be uniform. The question requires investigation with respect to delayed weld joint cracking, welding procedures are required to evaluate hydrogen cracking potential. General trends should be established for various processes, depths and weld joint types.

Specifying arbitrary hardness requirements for hyperbaric welding can be difficult and costly. Practical values need to be established for given applications and related to acheivable hardness for different underwater welding procedures.

5.3 AREAS OF RESEARCH AND DEVELOPMENT

The workshop, session II, will discuss the need for R&D in the following areas:

1.   Mechanized deep sea welding systems.

2.   Arc stability of TIG and GMA welding.

3.   Metal transfer and control algorithms for FCAW.

4.   Development of suitable consumables for TIG and MIG hyperbaric welding.

5.   Development of hyperbaric plasma welding.

6.   Development and assessment of quality criteria for the following processes.

7.   Hydrogen cracking tests for hyperbaric conditions.

8.   Evaluation of consequences and needs for rigorous hardness criteria for offshore constructions and pipelines.

V.B.   DEEP UNDERWATER WELDING - SESSION REPORT

H. Hoffmeister

5.4   INTRODUCTION

Underwater welding in deep waters has been and will be an important key to the exploitation of offshore gas and oil fields. The items considered have been grouped as follows:

1.   Range of depth of underwater welding and corresponding welding processes.

2.   Materials to be welded and requirements to be applied to the joints.

They have been discussed and the aspects of:

-   present state of the art
-   current R&D projects
-   future research needs.

5.5   THE RANGE OF DEPTH

Successful tie-in operations at 150m depth have been reported for North Sea in0tallations, using covered electrodes /1/. Subsequent work including fjord testing indicates that a reasonable weld joint quality can be achieved at considerably greater depth, using stick electrodes for a combination of this method with gas-shielded root pass welding.

Opinions differ as to the depth beyond which metallurgical problems will become significant. Reduced weld toughness would be expected due to an increased absorption of carbon and oxygen from the shielding atmosphere, which essentially consists of carbon monoxide. A concentration product $[\%C][\%O]$ depending on pressure only is shown in Figure 1 for deposits from basic electrodes (E8018-C1) containing various additions of deoxidants /2/. Taking the oxygen content at a chosen pressure of, for example, 30 bar, the product is about 0.01 $(\%)^2$. At 0.075% carbon the oxygen content will be 0.13% or 1300 ppm, and at 0.15%C about 0.067% or 670 ppm. The choice of a low carbon and a high oxygen content, or vice versa, appears to set a limit of sea depth beyond which covered electrodes cannot give a high quality deposit, carbon and oxygen being both deleterious with regard to notch toughness.

Hydrogen-induced cracking may arise from moisture present in electrode coatings and from infiltration of humid habitat gases into the arc atmosphere. The latter type of hydrogen contamination is common to all welding processes including inert-gas shielded methods. Infiltration of

surrounding gases is intensified by arc constriction under increased pressure. This is not merely a result of isostatic compression, which in itself imposes a handicap on covered electrodes producing a constant mass of shielding gas per unit mass of deposit. The effect is observed also with inert-gas shielded processes when the mass flow is increased in proportion to the pressure. Arc constriction becomes appreciable at 100 to 150m depth and is fully developed at about 300m. Beyond 250 to 300m depth there is no dramatic change of arc performance. However, it has been shown /4/ that arc atmosphere contamination by chamber gas depends on shielding gas flow rates, and that optimum flow rates have to be established for sufficient arc protection. The minimum of contamination corresponding to an optimum of flow rate is seen to increase.

On this background it would seem reasonable to restrict to depths greater than about 150m, since at smaller depth the problems can be overcome even in manual metal-arc welding. An upper limit is suggested at 500m depth. There are clear indications of a need of reliable welding procedures at 350 to 400m depth, both for purposes of repair and tie-in operations. Simulated testing has revealed that inert-gas shielded processes will work in a satisfactory manner up to 50 bar pressure or about 500m depth. On the other hand the safety and the efficiency of the welder would indicate a more conservative depth limit than the physics and metallurgy of the welding process. It is a fair assumption that mechanized remotely controlled welding will replace the human operator in future welding at great depth. Meanwhile, manual welding must be resorted to.

A limited depth has been indicated for welding with covered electrodes. In addition this process is not suitable for mechanization. It is therefore concluded that the workshop should concentrate upon continuous processes, stick electrodes being considered only with regard to proper range of application.

Of the inert-gas shielded processes, TIG and plasma-arc have the advantage of a separate choice of welding parameters and filler wire addition. In principle, therefore, these methods should be preferable to MIG welding of the root pass, while a higher rate of deposition might make MIG welding more attractive for the filler passes. Electrode wear and electrode contamination by spatter or by accidental contact with work-piece or wire are a worthwhile consideration, both factors being known to reduce the arc stability. On the basis of general principles the plasma-arc process would seem advantageous, since there is no risk of short circuiting and less danger of contamination by spatter. The ease of operation and ruggedness of plasma-arc guns will certainly also be factors of importance.

Arc stability and adequate penetration are requirements that have not been easy to meet in past experience with high-pressure MIG welding. Both requirements are strongly dependent on the operational conditions including the choice of shielding gas, and on the characteristics of the power source. These characteristics, e.g., the use of pulsed current, will of course also be important in TIG and PA welding.

Flux-cored arc welding should be considered as a separate method distinct from solid wire MIG welding. FCAW has the advantage of a good arc stability,

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which has to be weighed against the risk of slag entrapment sometimes reported as an objection against this method. At any rate the slag must be removed, which may not be an easy operation in narrow grooves. At this point it might be appropriate to look for slag-protected consumables available on the market properly adjusted for use under hyperbaric conditions. They have in general been designed for deposition under CO_2-shielding, which is unacceptable in deepwater welding. In the case of FCAW the core could conceivably be designed for purposed of arc stabilizing only, thereby reducing the volume of slag and the need of slag removal.

Mechanization, perhaps automation, of pipe butt welding is essential at 500M. The deepest identifiable present need. Such automated welding is desirable at lesser depths even where manual welding is practicable because of the quality of the results and the potential for speed. Manual intervention will be required to some extent.

The MIG, TIG and possibly Plasma welding processes appear to be the most suitable for such automatic welding. The plasma process is yet to be developed and may not work. Working equipment using TIG and MIG exist but these require further development and deserve funding.

The Manual Metal Arc (MMA) process works reasonably well down to about 500 ft but becomes increasingly insufficient and difficult to use with increasing depth. The performance of MMA could possibly be improved by development of the flux coating but it is doubted if such action would be worthwhile.

At depths deeper than 500M (1650 FSW) fusion welding may not be attractive but alternative diffusion bonding processes are increasing and may soon find application in such applications as sub-sea completions. Depth probabilities may soon exceed 750M.

Diffusion bonding processes are immune to metallurgical considerations and can be automated. Friction and explosion bonding are examples of other appropriate processes.

5.6 TYPES OF MATERIALS

Steel delivered to API Spec. 5LX60/65 covers the majority of applications of pipeline welding. These classes include a wide range of chemical compositions, depending on the methods used to obtain the required strength. There is a clear trend towards steel of a carbon content well below the conventional level of about 0.20%C.

Welding conditions for low-carbon, medium-strength steel should of course be chosen so as to avoid reduced toughness in the HAZ. This task, however, is common to welding of such steels in general, and should therefore not require any special attention for applications in underwater welding.

The most important feature of low-carbon steels is clearly the reduced risk of hydrogen-induced cracking. This applies to cracking of the HAZ (under-bead cracking) as well as to hydrogen fissures in the weld metal. A

beneficial effect of low carbon steels could also be a better notch toughness of the root pass due to a reduced carbon pickup from the parent plate. It is not known whether the concentration product (%C)(%O) referred to earlier for covered electrodes will be affected by the level of parent plate carbon; for inert-gas shielded processes a low initial carbon content would clearly be desirable.

Quality requirements to underwater welded joints should, in principle be equal to those specified for welding in open air. It may nevertheless be useful to discuss aspects of quality that are known to be affected by pressure.

Considering first the risk of HAZ cracking, it is well known that covered electrodes now available will give reproducible hydrogen levels H_{DM}*) down to 2-3 ml H_2 per 100 g deposit, or H_{FM}*) (Numbers refer to ISO 3690-77. Slightly lower values (approximately 90%) may be expected in analysis according to a method to be published by AWS. The terms H_{DM} and H_{FM} are defined by the International Institute of Welding (5)), about 1.5 ppm on a fused-metal basis. Values well below this level are readily obtained with inert-gas shielded processes. In underwater welding, infiltration of humid gases from the environment may easily raise the absorption of hydrogen to a level comparable to that considered normal 10 or 20 years ago. A qualification procedure for deep water welding should therefore include evidence of absence of cracking at a fairly high hydrogen level.

Similarly, hydrogen micro-fissures in the weld metal have been considered a matter of historical interest up to recent years. They may be back again in hyperbaric welds due to an increased hydrogen level. A similar type of weld metal defect has lately received considerable attention under a new label of "chevron cracking" /6;7/. So far they have been observed in submerged-arc deposits of a yield strength higher than about 500 MPa, at hydrogen levels H_{FM} higher than about 2 ppm, which may attain a high strength due to parent plate admixture, and in the filler passes where a build-up of the hydrogen level may be excepted.

A quality criterion often included in specifications of acceptance is the peak hardness, measured in procedure testing in the HAZ of the cap layer and sometimes also close to the root. Peak hardness is clearly related to the composition of the steel, mainly to the carbon content. It would in particular be useful to clarify the intentions of maximum hardness requirements: whether they are considered as an indication of safety against embrittlement and cracking in general, or as a precaution mainly applying to welded joints exposed to sour sulphur-containing media (stress corrosion cracking). In the former case permisible hardness levels should be adjusted according to the type of steel used, higher levels being acceptable in conventional medium carbon steels than in low-carbon grades. In the latter case hardness limits of, say 260 Vickers units would seem over-conservative in the absence of a corrosive environment.

5.6.1 Materials

Nothing can be done for existing constructions. New constructions should be designed to simplify hyperbaric repair or modification which might be

required. How far reduction in carbon equivalent, for example might be helpful in this connection is uncertain.

Carbon equivalent is not the only consideration - hardenability is also important and the two criteria may conflict. The effect of such limitations upon the properties of hyperbaric welds made by different processes, TIG, MIG, Wet, Dry etc. may not be uniform. The question requires investigation.

5.6.2 Hydrogen

Welding procedures required to evaluate hydrogen underbead cracking potential. General trends should be established for various processes, wet and dry, and depths.

Some owners presently specify maxhardness (peak) for welds. These requirements can be specially onerous for hyperbaric welding.

Specifying arbitrary hardness requirements for hyperbaric welding can be difficult and costly. Practical values need to be established for given applications and related to reliably achievable hardness for different underwater welding procedures.

5.7 AREAS OF RESEARCH AND DEVELOPMENT

The workshop has identified a need of research and development in the following areas:

1.   Mechanized welding systems in the habitat.

2.   Arc stability of TIG.

3.   Metal transfer and control algorithms for FCAW.

4.   Development and assessment of quality criteria for the following processes (diffusion bonding) for waterdepths > 500M.

            -      Explosive welding
            -      Friction welding
            -      Stud welding (arc and friction)

5.   Hydrogen tests for hyperbaric welding.

6.   Evaluation of consequence and need for rigorous hardness criteria for offshore constructions and pipelines (sheet).

7.   Rootpass welding techniques and choice of groove (narrow gap).

8.   Development of suitable consumables for hyperbaric TIG and MIG.

9.   Hyperbaric plasma as a welding tool.

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VI.A.   SHALLOW UNDERWATER WELDING – WHITE PAPER

J. Ibarra

6.1 ABSTRACT

Metallurgical Concepts are introduced to establish guidelines for the proper alloy modification of underwater welding consumables which are necessary to maintain or improve weld metal properties with increasing depth. The nature of pore formation and influence of pressure on porosity are described. The behavior of fatigue crack propagation through porous wet welds will be reported.
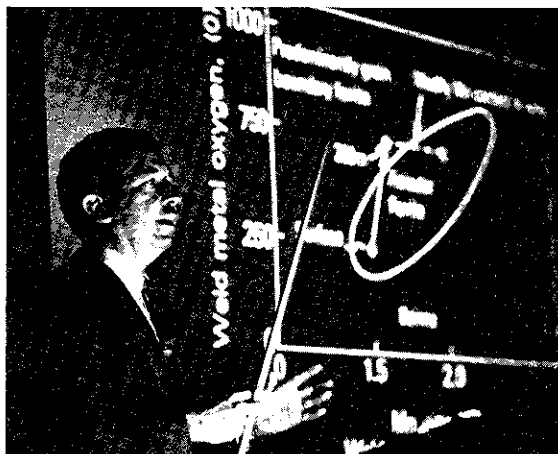
6.2 INTRODUCTION

Water and hydrostatic pressure are major environmental factors that make underwater welding different from surface welding. It is essential to understand the role of these factors if developments of new welding consumables and practice are to make advancements based on sound metallurgical fundamentals and engineering practice. Hydrostatic pressure increases at a rate of one bar for every 10 meters in depth. Both of these environmental factors influence the pyrometallurgical reactions (1-3) that control the weld metal composition. Water dissociates in the arc and introduces large amounts of hydrogen into the weld pool. This hydrogen can promote weld-metal porosity and hydrogen damage. The wet environment also influences the cooling rate during welding which affects the nature of the weld metal phase transformation.

Other reviews have been written (4-11), and have covered the various concerns in underwater welding. The continuous cooling transformation (CCT) diagram will be used in this paper as an instructional procedure to understand how the environmental factors of water and hydrostatic pressure will change the weld metal microstructure and thus the weld metal properties.

6.3 TYPES OF UNDERWATER WELDS

The specification for underwater welding (12) defines four types of welds, A, B, C, and O. Each type of weld has a set of criteria for the weldment properties that must be established during qualifications, and a set of weld soundness requirements that are to be verified during construction. Type "A" underwater welds are intended to be suitable for applications and design stresses comparable to those above water surface welds. Underwater dry habitat welds generally meet these criteria.

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Type "B" underwater welds are intended for less critical applications where lower ductility, greater porosity and other larger discontinuities can be tolerated. These requirements can usually be met by underwater wet welds. Type "C" underwater welds which need only satisfy lesser requirements than Types A, and B, and C are intended for applications where the load-bearing function is not a primary consideration. Type "O" underwater welds meet the requirements of another designated code or specification and is usually met only by underwater dry habitat welds.

This paper addresses the metallurgical principles, which have been established for low carbon steel surface welds, and extends them to the environment of water and hydrostatic pressure. With this approach improvement in weld metal properties can be achieved for type A habitat welds and type B underwater wet welds.

6.4 WELD METAL MICROSTRUCTURE

Low carbon steel weld metal microstructure consists of various fractions of ferrite, bainite (aligned carbides), and martensite. The weld microstructure shows characteristics of the solidification process with long dendritic grain growth from the edges of the weld pool leading up toward the center of the weld bead. There are three types of ferrite associated with weld metal. Grain boundaries can promote the formation of large grain boundary ferrite (BF), but are also the sites for the nucleation and growth of Widmanstatten or sideplate ferrite (SPF) which shoots out from the grain boundaries into the prior austenite grains. Acicular ferrite forms inside the grain and has a much finer basket weave structure. Other micro-constituents, such as pearlite, cementite and martenite, may also result. Figure 1 illustrate the nature of these various microstructures.

It is recognized that acicular ferrite is the microstructural constituent which gives a high resistance to cleavage fracture (13,14). Factors leading to an increase in the volume fraction of this constituent usually improve weld-metal toughness. The promotion of acicular ferrite should result from the proper amount of supercooling through alterations in weld-metal chemistry. The microstructures to be avoided are those with a high percentage of grain boundary ferrite, which result from a small degree of supercooling, and those which contain small amounts of martensite, which result from a large degree of supercooling.

The CCT diagram can be used to explain the relationship between the welding process and its the resulting cooling rate, the welding consumable and welding environment to the weld metal microstructure. Figure 2 illustrates a schematic CCT diagram. Also shown is a specific cooling rate which in this diagram intersects the ferrite nucleation curve at the acicular ferrite region. If the cooling rate was much slower, the cooling curve would intersect the grain boundary ferrite curve and if the cooling rate is much faster it would intersect the bainite or martensite curves. With this diagram it is possible to predict the trends for microstructural changes that would occur with a change in cooling rate.
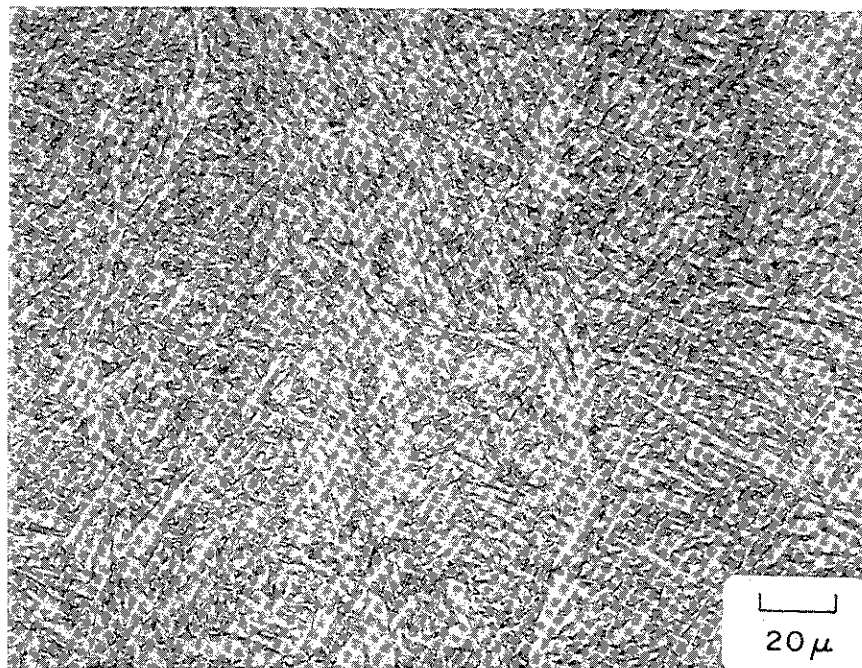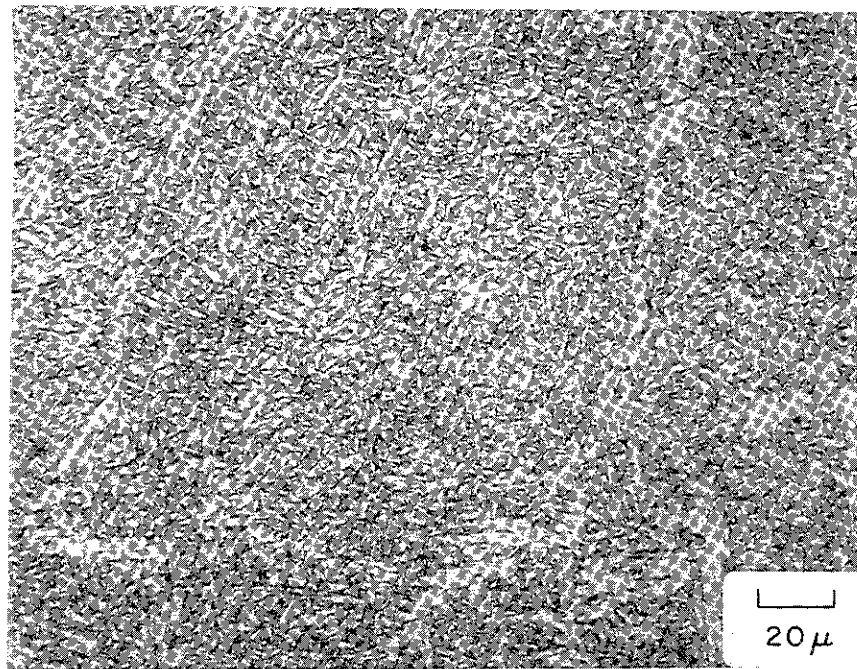
Figure 1.   Typical microstructures in low carbon low alloy steel weldments
showing: grain boundary ferrite (a); side plate ferrite (b);
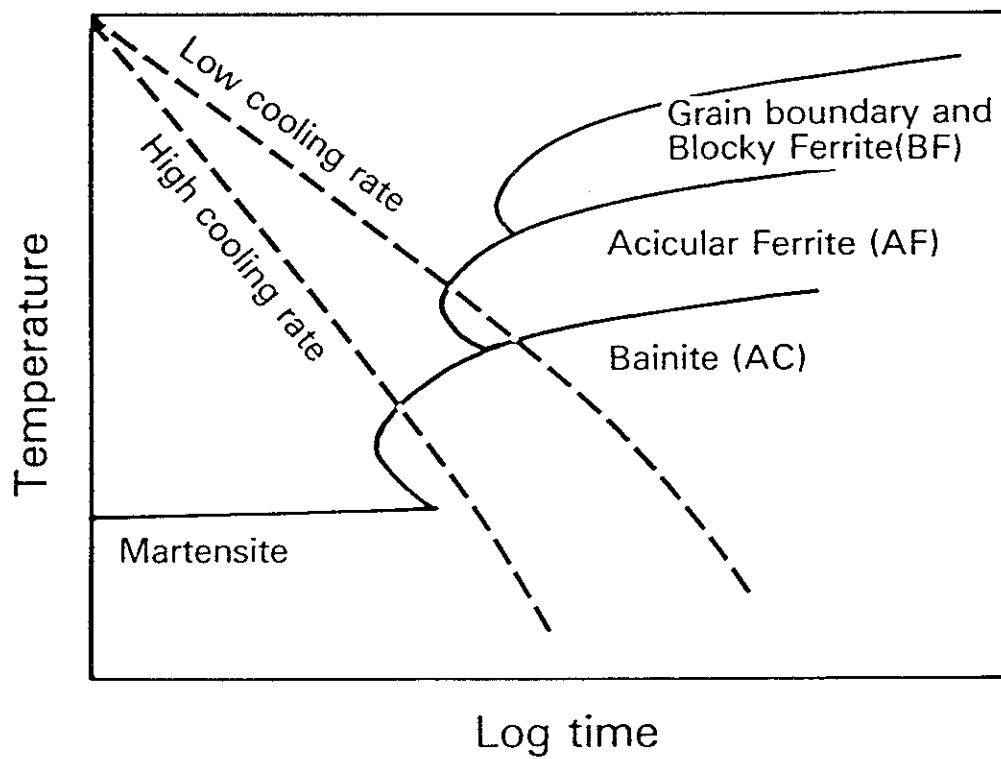acicular ferrite (c); and bainite (d).

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Figure 2. The influence of the cooling rate on the formation of specific weld metal microstructures.

A number of recent investigations (15-20) indicate that oxygen, which is in the form of inclusions, affects the weld metal microstructure and the mechanical properties. Ito and Nakanishi (21) observed that both high and low weld metal oxygen content weldments (with >500 ppm or <200 ppm) showed poor impact properties. Only the intermediate level oxygen welds (200 ppm to 500 ppm) produced tough acicular ferrite structures.

Cochrane and Kirkwood (10) studied the effects of weld metal oxygen on acicular ferrite formation and found that intermediate weld metal oxygen content (200-300 ppm) gave a primarily acicular ferrite microstructure, while side plate ferrite predominated at high oxygen contents (500 ppm). They concluded that weld metal oxygen variation affected the inclusion size distribution. Abson, Dolby and Hart (15) postulated that oxygen-rich inclusions can directly nucleate acicular ferrite, and in the absence of these inclusions, detrimental lath type structures (bainite) will form.

For high oxygen systems (>500 ppm), Indacochea and Olson (22) obtained predominantly grain boundary ferrite. Some evidence of the direct nucleation of the acicular ferrite phase on inclusions was observed. Increasing weld metal oxygen content, and thus the amount of inclusions, will move the transformation curve in figure 2 to shorter delay times.

Harrison and Farrar (23) reported that the austenite to ferrite transformation temperatures can be altered by the interaction of austenite grain boundaries with inclusions. A high inclusion concentration tended to reduce the austenite grain size, favoring grain boundary ferrite and side plate ferrite formation. Abson et al. (15) showed that a predominantly weld metal acicular ferrite microstructure is the result of the right inclusion size distribution. Liu and Olson (24) have determined the inclusion size distribution which can achieve optimum amount of acicular ferrite and mechanical properties.

Variations in weld metal oxygen and manganese will cause shifts in the nucleation curves in the CCT diagram as suggested in figure 3. Increasing weld metal oxygen promotes ferrite nucleation due to increasing in number of inclusions to be sites for heterogenous for nucleation and shift the curves to shorter time. This shift can potentially alter the weld metal microstructure. If this shift reduces the amount of acicular ferrite there will be a reduction in weld metal mechanical properties. Similar change in weld metal manganese content will also shift these curves. Increasing manganese causes an increase in hardenability and will shift the curves to longer times. Figure 4 illustrates that for a given heat input, and thus cooling rate, that there is a specific compositional range in weld metal carbon, manganese and oxygen to achieve optimum toughness. This region is illustrated by the thatched range in the figure. The shape of this range follows the work of Kikuta et. al. (25). Figure 4 will be used later to suggest compositional modifications for underwater welding consumables.

CCT diagrams can be used to understand and assist in modifying the alloy composition of the welding consumables to allow the acicular ferrite window in the CCT diagram to intersect the cooling rate and thus correcting for any variations in weld metal composition and for a severe quench due to the environment.

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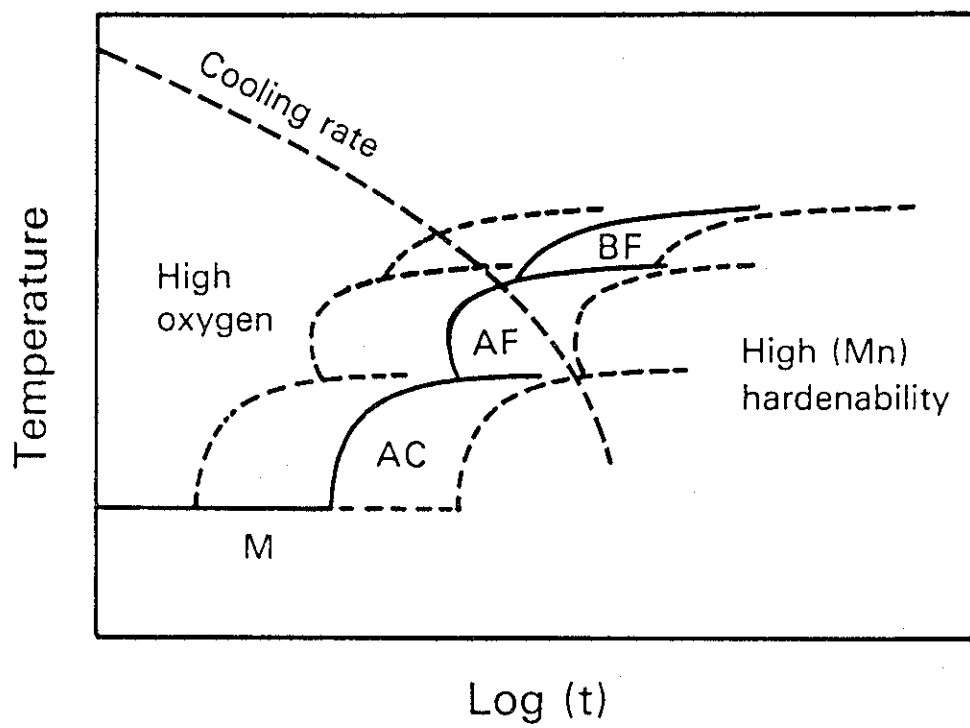
Figure 3. The influence of the weld metal oxygen and manganese contents on the weld metal hardenability.
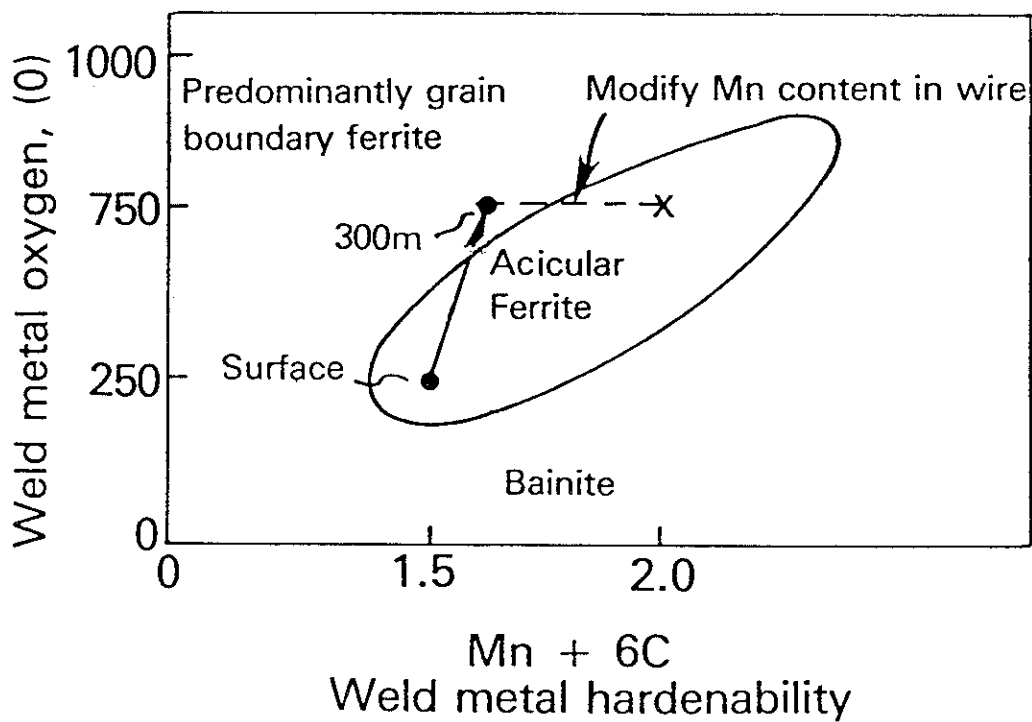
Figure 4. The range of high acicular ferrite content is illustrated on a plot of weld metal oxygen content versus weld metal hardenability. The weld metal composition shift due to changes in depth from the surface to 300 meters is illustrated. The proper manganese modification to bring the weld metal back to an acceptable microstructure is indicated.

In underwater welding we have to consider the source of weld metal oxygen. One source would be the decomposition of H_2O which is also a source for the weld metal hydrogen. The other potential source would be due to the decomposition of the carbonate addition to the electrode coating in the shielded metal arc electrode. Grong et al. (26) investigated the influence of SMA electrodes on the weld metal composition during hyperbaric welding of low carbon steel. A series of modified E8018-C1 electrodes were used which had systematic variations in ferrosilicon additions to the electrode coating. They found that both the weld metal oxygen and carbon contents increased with total pressure or depth. Figure 5 illustrates the weld metal oxygen content as a function of total pressure. Thirty bar pressure is approximately equivalent to 300 meters in depth. Figure 6 illustrates influence of pressure on the weld metal carbon content. Since both weld metal carbon and oxygen increase with pressure, the final influence on the weld metal microstructure and properties will depend on the relative influence of these elements which have direct opposite effects on the hardenability. Similar results have been reported for E7018 electrode used in habitat welding (27). Figure 6 also indicates no carbon pickup at usual depths for wet welding. However, it would be expected to increase at greater depths. Grong et al. (20) evaluated the CO reaction, which could result from the decomposition of carbonate in the welding arc, as being directly related to these increases in both carbon and oxygen. If the CO reaction is controlling, then there should be a relationship between the weld carbon, oxygen and partial pressure of CO. The partial pressure of CO is directly related to the total pressure by Dalton's Law resulting in the following equilibrium expression;

$$ K = \frac{P_{CO}}{(C)(O)} = \frac{f\ P_{TOTAL}}{(C)(O)} \tag{1} $$

where K is the equilibrium constant, f is the fraction of gas that is CO, P_{total} is the total pressure, (C) and (O) are the weld metal carbon and oxygen contents, respectively. Using the assumption that the weld metal composition has some information of a quench-in high temperature reaction, but also recognizing that the welding process is neither isothermal or at equilibrium, the plot of the product (C)(O) would be expected to be a linear function of the total pressure if this CO reaction is controlling. This behavior was observed for hyperbaric SMA welding down to the equivalent of 300 meter in depth. This suggests concern about using flux coating contain carbonates for hyperbaric welding. They also found that ferrosilicon additions to the flux did reduce weld metal oxygen but not sufficiently to alleveate this problem.

In both wet and hyperbaric habitat welding the weld metal manganese and silicon contents decrease with depth or pressure. Reported results are illustrated for wet welding in figure 7 and for habitat welding in figure 8. The reduction of weld metal manganese content will promote the shifting of the nucleation curves in figure 2 to shorter times and thus result in a predominately grain boundary ferrite microstructure and subsequent low toughness properties.
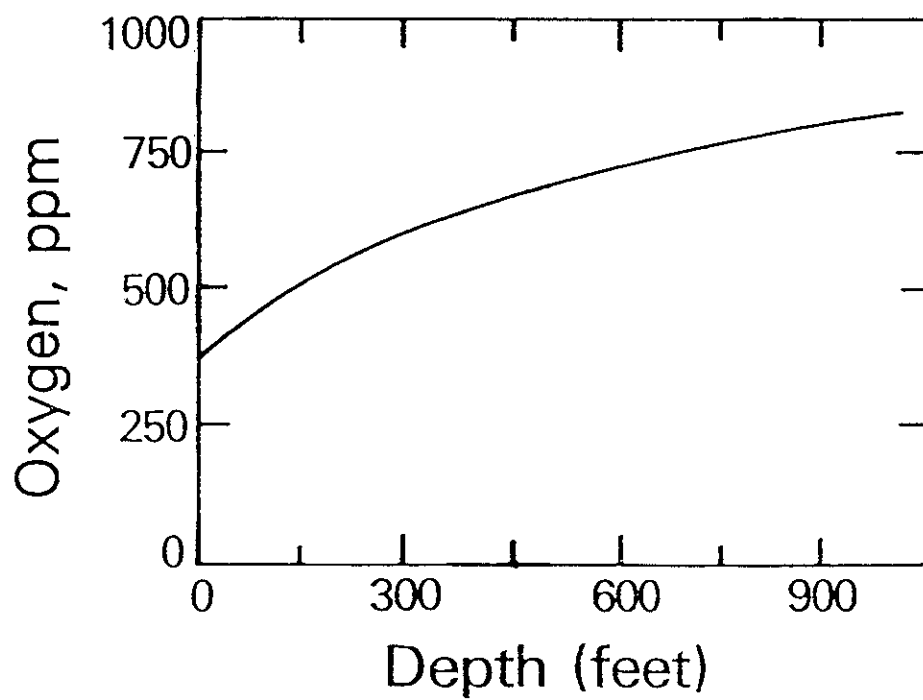
Figure 5. Weld metal oxygen content as a function of pressure for hyperbaric habitat, low carbon steel welds (3,26).
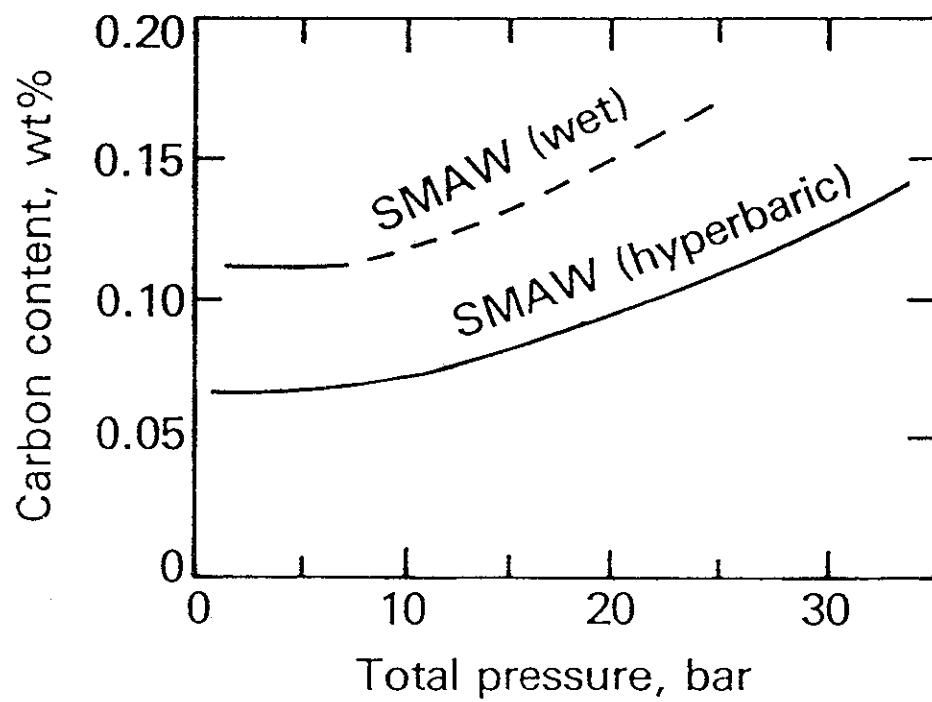
Figure 6. Weld metal carbon content as a function of pressure for both wet and hyperbaric habitat low carbon steel welds (3,26,27).

Since both the influence of increased weld metal oxygen and decreased manganese with increasing depth is to promote a higher fraction of grain boundary ferrite, the physical metallurgy concepts suggested here recommend that the manganese content in the welding consumable be increased with increasing depth for hyperbaric welding. These results suggest a small modification in electrode composition for each 30 meters of depth can assist in achieving properties. The electrode composition can be tuned to achieve the optimum microstructure by quantitative metallography.

In figure 4, which plots weld metal oxygen content as a function of weld metal hardenability, Mn+6C; the variation in weld metal microstructure is illustrated for the compositional changes suggested in figure 5, 6, and 8 for a habitat welding at a depth of 300 meters (30 bars). Notice the weld metal will change from primarily acicular ferrite to perdominantly grain boundary ferrite with the change in pressure from 1 to 30 bars. It is apparent that the fine weld metal acicular ferrite can be promoted by increasing the manganese content of the filler metal.

For underwater wet welding there is a major increase in the cooling rate which can better accommodate the shifts in weld metal compositions due to reduced hardenability. For hyperbaric type A welds the cooling time from 800 to 500°C, $\Delta t_{8/5}$, is normally in the range of 8 to 24 seconds, whereas the underwater, type B and C, wet weld experienced $\Delta t_{8/5}$ in the range of three to seven seconds (27). Mathisen and Gjermundsen (27) have also measured the variation of cooling rate as a function of nature of the convection of water. The manganese of the welding consumable can again be modified to achieve a microstructure with favorable microstructure.

Once the desired acicular ferrite microstructure has been achieved, even higher weld metal toughness can be produced by reducing the size of the acicular ferrite lath. Alloy additions such as titanium and boron can be introduced to the weld metal to reduce the acicular ferrite lath size. In this manner further fine tuning of electrode composition can be achieved which will produce the optimum weld metal properties.

6.5 WELD METAL POROSITY

Weld metal porosity is the most common defect for all welding processes, but is major concern in welds that are made underwater. The amount of porosity determines whether a wet weld is a type B, or C weld. Pore formation results from entrapment, supersaturation of dissolved gas or gas producing chemical reactions. The nature and amount of weld metal porosity involves at least three competing time dependent processes (28-32). These processes are the nucleation of pores, the growth of pores, and the transport of pores. The physical requirement for pore formation is that the sum of the partial pressure, p_g, of soluble gases must exceed the sum of the following pressure terms;

$$P_g > P_a + P_h + P_b \qquad (eq.\ 2)$$

where P_a is the atmosphere pressure, P_h is the hydrostatic pressure and P_b is the pressure increase due to the curvature of the pore and is given by the following equation;
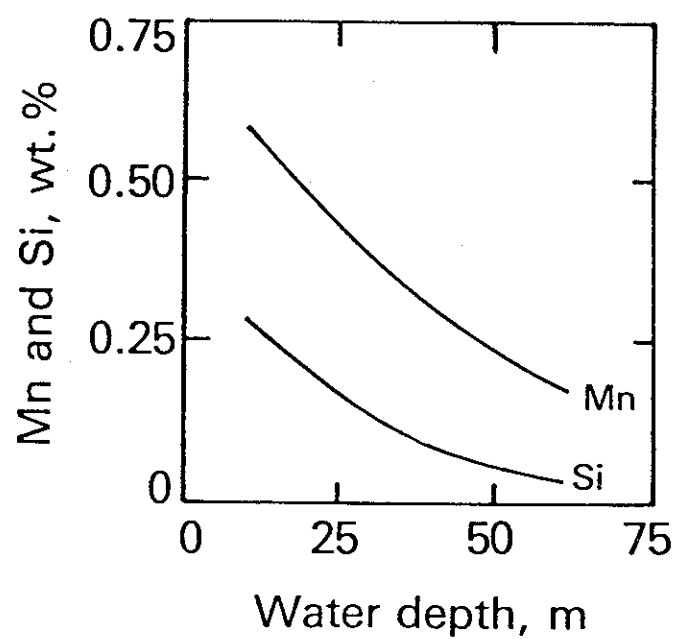
Figure 7.   Weld metal manganese and silicon contents as a function of water depth for wet low carbon steel welds (27).
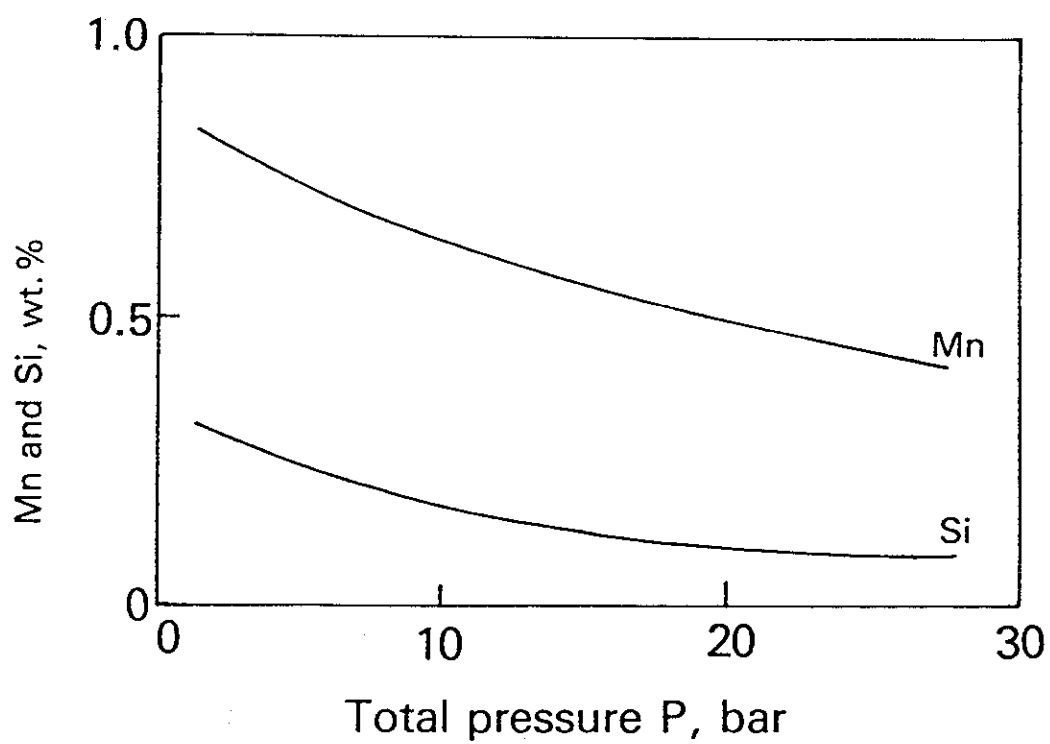
Figure 8. Weld metal silicon and manganese contents as a function of pressure
for hyperbaric habitat carbon steel welds (3).

$$P_b = \frac{2\gamma}{r} \tag{3}$$

where, γ is the surface tension between the melt and the gas in the pore and r is the radius of pore curvature. But for underwater welding P_h is the controlling term since it is a strong function of depth.

Pore formation must also encounter and overcome the kinetic activation barriers, such as nucleation. There is a critical pore radius, r_c, which if exceeded the pore will homogeneously nucleate and grow spontaneously to unlimited dimensions. Nikiforov and Redchits (28) have reported an expression, I, for the nucleation of pores from a solution which is absent of non-wettable interfaces:

$$I = A \exp \left(-\frac{4}{3} \pi \frac{r_c^3 \gamma}{kT} \right) \tag{4}$$

where A is a constant. Expressions for this critical radius have been developed. A common criteria for the desire to form a gas bubble is given as:

$$r_c \geq \frac{2\gamma V}{kT \ln\left(\frac{P_g}{P_\infty}\right)} \tag{5}$$

Where V is the atomic volume of the gas phase, P_∞ is the solubility of the metastable gas phase, and kT has its usual significance. The formation of a gas nucleus is only possible at a definite supersaturation ($P_g/P_\infty > 1$). P_∞ is a function of the hydrostatic pressure and thus depth.

A more likely situation is for heterogeneous nucleation of pores where solid/liquid interfaces becomes a lower barrier energy site for nucleation. Heterogeneous nucleation can be achieved by less gas volume than experienced by homogeneous nucleation. Sapiro (33) introduced a modified criteria for heterogeneous pore formation. This modified equation is given:

where θ is the contact angle between the gas and the substrate and β is a coefficient which empirically relates liquid metal adhesion to the substrate. Considering the contact angle is zero the gas nucleus has the form of a sphere, touching the solid surface at only one point. The condition for pore formation for this homogeneous nucleation using Sapiro's equation is given by:

$$P_g \geq P_a + P_h + 2\beta\gamma \tag{7}$$

Therefore the surfaces of dendrites and precipitated crystals, which are well wetted by the liquid metal and which can potentially form contact angles close to zero create high capillary resistance, which inhibits the formation of gas nuclei. The presence of poorly wetable non-metallic inclusions in the weld metal will facilitate the formation of gas nuclei and porosity. This also suggest that the amount of porosity in underwater welds is indirect related to the amount of inclusion (weld metal oxygen) and cleanliness of the weld metal.

The influence of depth can be seen in the factor P_g/P_∞. The schematic solubility diagram is illustrated in figure 9. In this figure the solubility of hydrogen as function of temperature is assumed for two hydrostatic pressure (1 atm and 10 atm). It is assumed the solubility curve maintain its shape with increasing pressure but is displaced by pressure to the right and up. This is consistant with the increase in melting temperature, T_{mp}, with increasing pressure. If we assume that P_g is the amount of hydrogen dissolved in the melt at the highest temperature of the welding process, T_{wp}, then it is obvious that as solubility drops with temperature, the ratio P_g/P_∞ gets increasingly larger and the critical radius, as described in equation 5, and the activation energy factor, as described in equation 4, gets smaller. Thus making the rate of pore formation greater as the temperature drops in the weld pool. The actual temperature for pore formation is probably near the solidification temperature. Comparing the expected P_g/P_∞ for the two different hydrostatic pressure situations, it becomes apparent that $(P_g/P_\infty)_{10atm}$ is less than $(P_g/P_\infty)_{1atm}$ where as the liquid temperature approaches the melting temperature. This simplified analysis suggests that as the depth increases, the critical pore radius to nucleate a pore is larger and it becomes more difficult to form pores during welding, so there should be less porosity in the weld metal. This apparent reduction in weld metal porosity may not be an advantage for it means that the hydrogen is having difficulties in leaving the weld pool and weld metal hydrogen content is left at some extremely high levels. As the amount of porosity decreases, the susceptibility for hydrogen damage may increase. This prediction of lower porosity is not observed for underwater wet welding with indreasing depth (34).

Two possible explanations for this discrepancy between theoretical prediction and observation discrepancy is that (i) the hydrogen solubility reaction is more complex than the classical model and (ii) the major influence to the hydrogen concentration is at the solidification interface due to the drastic change in solubility with the change in phase.

Christensen (33) and Salter (36) have both reported that water vapor is equally as effective as hydrogen in the production of weld metal hydrogen. A combined partial pressure, P_w, which is given as; $P_w = P_H + P_{H_2O}$, has been suggested for correlation of weld metal hydrogen to the shielding gas. Also it has been found that the hydrogen pickup in the weld metal does not follow Sievert's Law. The weld metal hydrogen content fell short of the expected equilibrium values as a function of pressure. The pressure dependence of the weld metal hydrogen content does not even take a parabolic form, suggesting complex gas-metal reactions which probably involve different reactions at different positions in the weld pool relative to the center of the heat source. The hydrogen content starts out with an apparent parabolic shape with increasing pressure but becomes linear, in some cases nearly flat,

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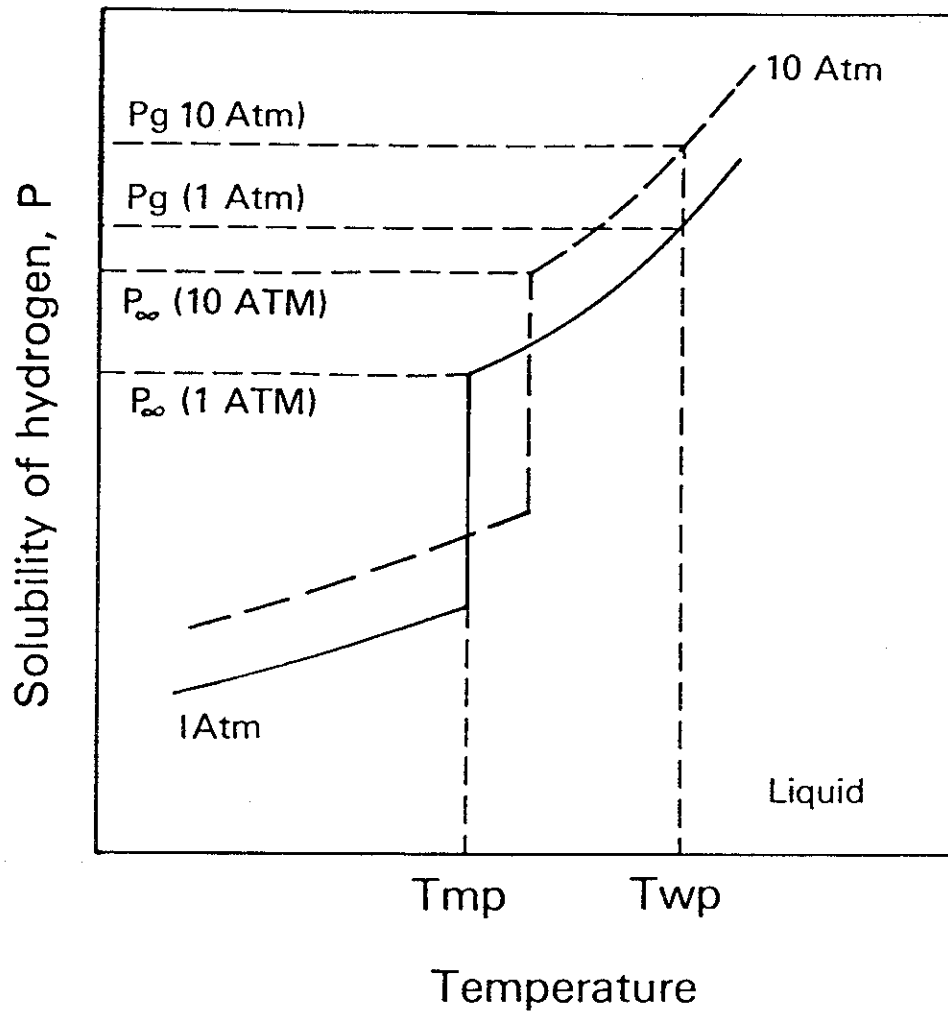
Figure 9. A schematic of the solubility of hydrogen as a function of
temperature for two pressure (1 atom and 10 atom). Also indicated
is the maximum amount of gas dissolved. Pg, at the pick weld pool
temperature during welding for both pressures.

over a large pressure range above 10 atms. This linear dependency can suggest a monoatomic hydrogen--metal reaction instead of the normal diatomic hydrogen reaction.

Pokhodnya et al. (29) suggests that the gas concentration ahead of the solidification front, $C_g(\chi)$, needs to be considered in these analyses and describe this concentration by the equation:

$$C_g(x) = C_o \left[1 + \frac{1-k'}{k'} \exp \left(\frac{-RX}{D_1} \right) \right] \qquad (7)$$

where C_o is the solubility of the gas in the liquid metal, χ is the distance from the solidification front, k' is the distribution coefficient, R is the rate of solidification, and D_1 is the diffusion coefficient in the liquid. The maximum gas content is observed at the solidification front, and it is equal to C_o/k'. It is at this location that pore formation most likely occurs. This expression suggests that the weld metal hydrogen content, C_o, needs to be adjusted if pore a heterogeneously nucleated at the moving solid/liquid interface. Uda, M. et al. (30) tested these concepts using the Fe-H system. They found that from the viewpoint of solidifiction theory even if the content of dissolved hydrogen in the bulk of molten iron is low, hydrogen may be concentrated in the front region of solidification interface.

Gorshkov (31) reported that the growth rate of the pore is a function of the isobaric pressures of the gases, the surface tension, and the viscosity of the molten metal. The radius or size of the pore will depend on the time during which the metal is in the molten state. This time is controlled by the welding conditions, and especially by the heat input. Gas bubbles develop as a result of the diffusion of gases into them and then are distributed along the sides of the welded joints by the convection currents. Based on this theory Gorshkov (32) made some theoretical considerations about the mass transport associated with pore formation.

Two possible methods to reduce weld metal porosity with depth for wet welding is (i) to make specific elemental additions to the weld pool which getter the hydrogen by forming hydrides, and (ii) to alter the welding parameters to reduce pore formation. Adding titanium and zirconium to the weld pool should assist in the reduction of porosity since they are known hydride formers. The influence of travel speed on pore formation has been studied by a number of investigators (37-39). Tretyakov and Gorshkov (38) and Miller and Salter (39) reported that with increasing travel speed the pore concentration goes through a maximum. Milner and Salter (37) suggests a relationship between the product of travel speed (S) and bead area (A) and the amount of gas absorbed per unit volume of weld metal. For decreasing values of the product (S A) the gas absorbed per unit volume of weld metal increases for the same gas partial pressure. This means that with small beads and slow welding speed the amount of gas absorbed per unit volume of weld metal is high. The faster freezing rate of the smaller short circuiting arc weld allows less time for gas desorption and cause more bubbles of gas to be trapped before they rise to the surface of the weld pool. This relationship holds significance for many of the practices used in underwater wet welding which produce small weld deposits.

Woods, (40,41) reported that porosity increased with increasing welding current since the welding current raised the average surface temperature of the weld pool and enlarged the area of the hot granular zone over which the hydrogen absorption take place. In underwater welding the relationship between porosity and welding current is strongly influenced by the type of moisture resistance coating on the electrode. The influence of arc length was also studied (40,41) and the gas pickup increased as the arc was lengthened. In general terms, the hydrogen absorption and therefore porosity levels in welding should be minimized by using a low current, a short arc, and fast travel speed.

6.6 FATIGUE AS A FUNCTION OF POROSITY

The designers of offshore structures are usually concerned with the initiation and growth of fatigue cracks in fracture critical members. The cyclic fatigue stresses will develop with any natural sea movement and will increase during storms. It is important that the underwater repair of weldments be designed so that the possibility of the initiation and growth of such cracks is minimized. There is concern that the growth of fatigue cracks in underwater welds is higher because of noted decreases in fracture toughness and because of the presence of varying amounts of porosity. Drilling the tip of a fatigue crack is a common field technique used to prevent further crack growth. The presence of porosity in weldments can be beneficial because the pores act as pinning sites for fatigue cracks to retard or stop their growth.

Matlock et. al. (42) have shown that the presence of some porosity could be beneficial at low stresses because it retarded fatigue crack growth in surface habitat and underwater wet welds. The studies were conducted on multiple pass steel weldments which were fabricated with E6013 electrode having three different waterproof coatings. In comparison to normal wrought ferrite-pearlite steels, all experimental welds exhibited lower growth rates for low values of ΔK, but tended to be higher than the wrought alloys at high values of ΔK particularly in wet welds.

Because the microstructure, hardness, and chemical compositions (except for Mn and O) were similar for all of the welds, the fatigue properties shown primarily reflect the differences in porosity. The surface and hyperbaric habitat welds generally do not have the porosity shown in underwater wet welds. At low ΔK the wet underwater welds have the most fatigue crack growth resistance. The large number of pores act as pinning sites for the advancing fatigue crack front. Increaed porosity in a weldment yielded lower the fatigue crack growth at low ΔK.

At high ΔK the crack growth rate is much greater the higher the porosity content. The implication being that at higher stresses the sample acts more like tensile tests and the high number of pores act to reduce the cross sectional area and thus allow the cracks to propagate at a high rate. It can be concluded that the presence of porosity can be beneficial in cases where the weldments are subjected to low stresses and where other propeties such as fractures toughness do not deteriorate.

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6.7 SUMMARY

A better understanding of the role of hydrostatic pressure and water has been attained which should facilitate the development of new underwater welding consumables. Such electrodes can be "fine tuned" with alloying additions which optimize the microstructure by:

1. Changing the position of the CCT diagram to allow for cooling to occur through microstructure regions where mechanical properties are optimized.

2. Reducing the weld metal hydorgen content to allow for decreased porosity and the improved weld metal properties.

6.8 ACKNOWLEDGEMENT

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6.10   DESCRIPTIONS AND RECOMMENDATIONS FOR
SHALLOW UNDERWATER WELDING CONCERNS

A group of fifteen engineers meet for approximately six hours to discuss engineering concerns associated with shallow underwater welding and to obtain a prioritized list of research topics to achieve solutions to these concerns. The group have a broad representation from diving companies, oil companies, fabricators and academia. Twelve concerns were identified and are listed as follows in a prioritized list:

1.   Influence of Metallurgical Factors in the Process of Wet Welding and their Application to the Formulation of Wet Welding Electrodes

2.   Shallow Water Welding Techniques

3.   Crack Resistance of Wet Welds as Related to Piping Porosity and Orientation

4.   Consequences of High Hardness in Wet Welds

5.   Wet Welding of New Advanced Steels and its Relationship to Carbon Equivalent Empirical Expressions and Strengthening Mechanisms.

6.   AWS Specifications for Underwater Welding Electrodes

7.   Handbook for Underwater Welding Techniques and Technologies

8.   Mechanical Properties of Type B Underwater Wet Welds

9.   Review Essential Variables for Welding Procedure Qualifications

10.   The Effect of Heat Input on Hot Tap Weld Performance

11.   The Significance and Measurement of the Hydrogen Content of Ferritic Wet Welds

12.   Evaluation of Bend Test Requirements for Type B Underwater Wet Welds

A description and recommendation are given for each concern. The priority was established by a prioritized vote by each member of the group. The prioritizing of these projects may represent the makeup of this group and should be further evaluated to make sure it represents the overall needs of the Marine (ship and offshore) Industy, U.S. Navy and the regulating agencies.

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6.11 INFLUENCE OF METALLURGICAL FACTORS IN THE PROCESS OF WET WELDING AND THEIR APPLICATION TO THE FORMATION OF WET WELDING ELECTRODES

Water and hydrostatic pressure are major environmental factors that make underwater welding different from surface welding. It is essential to understand the role of these factors if developments of new welding consumables and practice are to make advancements based on sound metallurgical fundamentals and engineering practice. Hydrostatic pressure increases at a rate of one bar for every 10 meters in depth. Both of these environmental factors influence the pyrometallurgical reactions that control the weld metal composition and microstructure. Water dissociates in the arc and introduces larger amounts of hydrogen into the weld pool. This hydrogen can promote weld-metal porosity and hydrogen damage. The wet environment also influences the cooling rate during welding which affects the nature of the weld metal phase transformations.

6.11.1 Recommendations

Study how factors like cooling rate, heat input, and steel process variables affect wet underwater weld metal microstructure. Characterize typical welding environments to establish ranges of ambient temperatures, depth, and cooling rates usually encountered. Metallurgical concepts need to be determined to establish guidelines for the proper alloy modification of underwater welding consumables which are necessary to maintain or improve weld metal properties with increasing depth. For example, for a given material based on typical values of arc temperatures, ambient water temperature, and geometry of welded section, a range of cooling rates can be estimated. These in turn can be used to predict microstructure within certain broad limits. Also the influence of depth on weld metal composition needs to be better established.

Based on the above information it may be possible to tailor-make wet-welding electrodes for certain applications by incorporating elements to compensate for a given effect.

6.12 SHALLOW WATER WELDING TECHNIQUES

At present the oil industry has various underwater welding techniques available to it. These techniques include: 1. Cofferdam, 2. Hyperbaric, 3. Dry Box (Spot Welding), 4. Wet Welding, and 5. Friction Welding. The selection of one of the above techniques depends on the environmental and geometric characteristics at the weld site as well as the required mechanical properties of the weld. Quantitative techniques need to be established to assist in the selection of a shallow water welding technique. Such an analysis has to consider economics, as well as weld integrity, as a primary factor.

6.12.1 Recommendation

It is recommended that a study be undertaken to quantify when to select a particular technique and to indicate its expected cost. These techniques should be reviewed according to Table I. Friction welding is not included in Table I since its applications are limited and justify a separate discussion.

6.13 CRACK RESISTANCE OF WET WELDS AS RELATED TO PIPING, POROSITY, ORIENTATION

The Colorado School of Mines study (ref. 1) of crack propagation in wet weld metal was based on a groove weld made on plate in the 2G position at 10 meters. The test crack was propagated in only one of several directions that could have been chosen. Porosity in the weld specimen was approximately spherical.

Their have been two recent observations:

1.   As depths increase, wet weld porosity tends to become more elongated (piping porosity rather than spherical).

2.   The crack resistance of wet welds depends on piping porosity orientation and the orientation of the porosity is not the same for all weld positions. Since the wet weld crack resistance is greater in one direction than another, better knowledge of the phenomena is essential in developing optimum underwater repair designs. This requires developmental work, such as wet welds made in four positions at several depths down to about 100 meters.

6.13.1 Recommendation

Perform crack propagation studies, both fracture and fatigue, on wet welds with characterized porosity and perform this analysis such that all the important porosity orientations have been considered (see ref. 42 from Section VI.A.).

6.14 CONSEQUENCES OF HIGH HAZ HARDNESS IN WET WELDS

The high heat affected zone hardness levels caused by the rapid quench of wet welds raises many concerns; among them reduced fatigue life, hydrogen embrittlement, and initiation sites for brittle failure. This has prevented many companies from using wet welding even in non-structural applications. In most wet welded repairs, the location of maximum stress is at the top of the weld in this hardened heat affected zone. It is therefore crucial that this HAZ concern be addressed, before improvements in weld metal microstructure and fracture toughness can be of any great use. Several studies into this question have been conducted, and the results of these studies should shortly be in the public domain.

6.14.1   Recommendations

(1) The existing information about the influence of high HAZ hardnesses on the integrity of wet weld needs to be compiled and analyzed.   (2) If necessary, additional work needs to be done to clearly understand this concern.   (3) Factors to be considered in addition to hardness levels, include level of restraint, amount of diffusible hydrogen available, the temperature of the environment, and the amount of hydrogen available from the environment.

6.15   WET WELDING OF NEW MICROALLOYED STEELS BASED ON CARBON EQUIVALENT EXPRESSIONS

New steels have been developed using combinations of thermo-mechanical processing and different chemistries not characteristic of the steels which have been used for producing the majority of the current underwater welding data.   The API Offshore Structures Materials & NDE Subcommittee has a draft in preparation for such steels.   Such steels are being considered for offshore platforms in the Gulf of Mexico.   It is the view of most of the members of this committee that these steels will become the standard of the industry within a short time after issuance of this standard.   ASTM A-710 steel as a example of such a candidate material.   Similar low carbon pipeline steels which can have a capability of meeting NACE Specifications for sour service without stress relief are being developed and finding increased demand.   These steels are likely more weldable in the wet for hot taps and external patching.

6.15.1   Recommendations

A selection of the most promising materials should be made by alloy composition and processing which would represent the different generic classes of yield strength grades (42, 50, and 60 ksi) at maximum thicknsses.   These selected material will be evaluated for underwater wet weldability.

Evaluation of the concept of using carbon equivalent expression for determination of wet weldability shall be part of this investigation. Specifically users should be advised as to whether the carbon equivalent formula of IIW, P_{cm}, or some other empirical expression is best for determining the suitability of the material for wet welding.   Testing should include the minimum of the requirements of AWS D3.60-83 specifications.

6.16   AWS SPECIFICATIONS FOR UNDERWATER WELDING ELECTRODES

New types of electrodes have been developed by various companies stemming from their underwater welding applications.   These welding consumables with their specific application should have their own classifications and specifications.

Electrodes should be produced under a classification grouping of their own.   It is therefore recommended that AWS gather the information available from whomever may posses it, on these electrodes.   Research is suggested which would assist in characterizing and grouping of these electrodes into a new classification grouping for underwater welding applications.   The question of how depth should be considered in a new classification needs to be determined.

6.17 HANDBOOK FOR UNDERWATER WELDING TECHNIQUES & TECHNOLOGIES

An updatable underwater welding handbook for contractors would be a major contribution to the Marine Structural industry. It would be desirable to make such a handbook, in conjunction with the databases from diving companies, fabricators and research laboratories. The handbook would not use proprietary information, such as including developments yet to be presented or marketed, but should be focused on current accepted wet and dry methods, processes, metallurgical facts, AWS D3.6 specifications, steels, etc. Since economics is not usually addressed in the selection of underwater methods they should be shown where applicable. The handbook should educate the user of underwater welding and should provoke new interest in research and development by showing areas that have insufficient information. If a handbook can be developed with a worldwide sharing of information, then a more thorough understanding of advantages and limitations of the various underwater welding practices can be accomplished. This handbook would reduce the amount of redundant underwater welding research which is very expensive. The handbook should promote better industrial acceptances of underwater welding and thus increase its overall usage.

6.17.1 Recommendations

1.   Inquires need to be made to the diving companies, fabricators, licensing, and regulatory agencies as to the their willingness to contribute information for this handbook.

2.   If the inquires are positive then guidelines and editors for the handbook need to be identified and the development of the handbook should proceed.

6.18 MECHANICAL PROPERTIES OF TYPE B UNDERWATER WET WELDS

The specification for underwater welding (ref. 2) defines four types of welds, A, B, C, and O. Each type of weld has a set of criteria for the weldment properties that must be established during qualifications, and a set of weld soundness requirements that are to be verified during construction. Type "A" underwater welds are intended to be suitable for applications and design stresses comparable to those above water surface welds. Underwater dry habitat welds generally meet these criteria.

Type "B" underwater welds are intended for less critical applications where lower ductility, greater porosity and other larger discontinuities can be tolerated. These requirements can usually be met by underwater wet welds. Type "C" underwater welds which need only satisfy lesser requirements than Types A, and B, and C are intended for applications where the load-bearing function is not a primary consideration. Type "O" underwater welds meet the requirements of another designated code or specification and is usually met only by underwater dry habitat welds.

The acceptance criteria for an AWS D3.6-83 Type B weld are clearly defined. However, the mechanical characteristics (and therefore the applicability) of a Type B weld are not defined.

6.18.1 Recommendations

1. Determine the mechanical properties (and thus the applicability) of a Type B weld.

2. Identifying those mechanical properties which are relevant to the application (i.e. fracture toughness).

3. Identify appropriate categories of Type B welds for testing, (i.e. types of steel, types of electrodes, depth), habitat, wet. etc.

4. Test for appropriate mechanical properties by selected category.

Ref. 2. American Welding Society, "Specification for Underwater Welding", ANSI/AWS D3.6-83, Miami, FL (1983).

6.19 REVIEW ESSENTIAL VARIABLES FOR WELDING PROCEDURE QUALIFICATION

The essential variables for the qualification of welding procedure and welder performance qualification need to be reviewed and updated. The initiation for this study should first concentrate on the variables listed in AWS D3.6 specifications on "Underwater Welding".

The essential variables listed in AWS D3.6, specification and their ranges, were based on what was considered to be important at the time D3.6 specification was written. Since this time, various companies have gained considerable experience in underwater welding.

6.19.1 Recommendation

Research needs to be done to establish what variables should be considered as "essential" and what their allowable ranges should be. These allowable ranges should be based on actual test data not just educated guesses. These findings should be carefully incorporated in the revised AWS D3.6 specifications.

6.20 RESEARCH ON THE EFFECT OF HEAT INPUT ON HOT TAP WELD PERFORMANCE

At present, there is a difference of opinion within the industry as to the affect of heat input on the performance of underwater hyperbaric hot tap welds. Many companies feel that a hot tap on a line with low temperature effluent (below 50F) will result in unacceptably hard heat affected zones. These zones are ideal sites for initiation and propagation of cracks. Electric resistance pads are sometimes required to provide some heat input but it is felt that the "heat sink" effect provided by the liquid negates these efforts. Due to the significant cost involved in the implementation of this controversial requirement, the committee recommends that the need for this requirement be substantiated.

6.20.1 Recommendation

It is proposed that a literature search be performed to gather existing data on this topic. It is also recommended that additional research in the form of mock-up testing be conducted on various grades of steel to quantify the type of heat input required and the establishment of preheat requirements for given grades of steel.

6.21 SIGNIFICANCE AND MEASUREMENT OF THE HYDROGEN CONTENT ON FERRITIC WET WELDS

6.21.1 Questions

The following questions on the influence of weld metal on the wet weld integrity need to be answered.

1.1 How much does the hydrogen content present in ferritic wet welds vary with depth?

1.2 How long after making a wet weld will there be sufficient hydrogen available to present risks of hydrogen cracking?

1.3 How much variation is there in the hydrogen levels of weld deposits produced with different company's proprietary electrodes?

1.4 If a hydrogen determination is to be included as an essential variable for procedure qualifications, what method should be used to measure it and what would be the acceptable limit.

6.21.2 Recommendations

2.1 Review available methods for determining hydrogen content and decide on most practical method for routine tests. Alternatively, develop a new test method.

2.2 Make a series of wet welds at various depths with different currently available proprietary electrodes and determine hydrogen content by method identified in 2.1.

2.3 Based on hydrogen levels found in 2.2 calculate time to reach a conservative safe residual hydrogen level for various weld configurations.

6.22 EVALUATION OF BEND TEST REQUIREMENTS FOR TYPE B UNDERWATER WET WELDS

AWS D3.6-83 requires Type B welds pass a 6T bend test. Today's state-of-the-art wet welding electrodes will pass bend tests over smaller radii (i.e. 4T) at shallow depths (i.e. less than 16 meters). What requirements for bend testing need to be established to make the bend test a meaningful procedure?

6.22.1 Recommendations

Determine minimum bend radius state-of-the-art wet welding electrodes will pass at 10 meters depth. Determine at what increased depth failure begins to occur at this minimum radius; then determine the minimum radius required for passing at this deeper depth. Repeat this once more so that three minimum bend radii are established for three corresponding depth ranges.

P. DeLaune

7.1 INTRODUCTION

This paper was written to discuss
Quality of Underwater Welding, and
specifically the subject of inspection.
On the positive side, the American Welding
Society recently published a, "Specification
for Underwater Welding - D3.6", to provide
users with a convenient method to contract
for services at a known quality level.
However, the type of weld selected and the
supplimentary methods of examination are
the responsibility of the customer; and the
choice of weld type and inspection method
for a given job is a complex issue depending
on a number of factors. This workshop will
help to provide information which will make
the choices less difficult. Since many of
the workshop participants are not in the
role of users of the specifications, so
the inspection session should not discuss
the subject solely in the context of that
document.
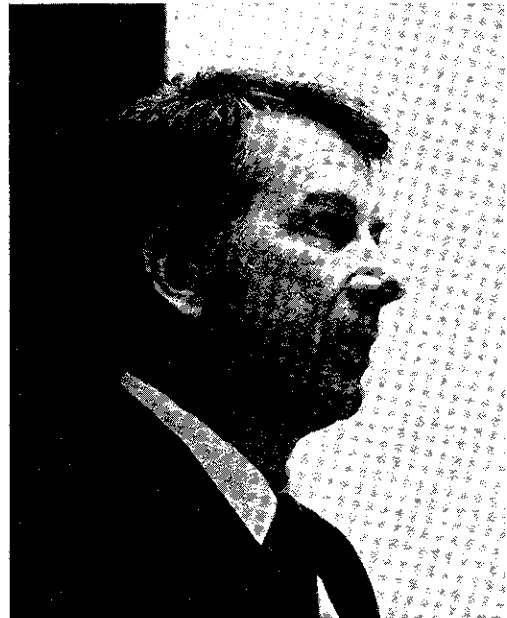
The time is approaching when welds underwater will be produced remotely;
probably in an inert gas or in the water. Until that time however, welds
underwater will likely be produced by divers, and the subjects of diving and
welding will not be easily separated. In any case, diving and underwater
welding share the science of gasses and would-be inspectors should consider
how.

7.2. GASES

There are three gasses to consider. Water is displaced with background
gas; the diver inhales breathing gas, and surrounding the arc is ambient gas.
Diving modes are created in response to the increased toxicity of gas with
depth; and each mode has associated with it, times and depths where, today,
safe diving is possible. When welding is considered, depths are modified to
account for achievable weld properties. We have also to consider the ambient
gas in the presence of combustibles, a heat source, and oxygen greater than 5
to 8 percent can represent a fire hazard. Each gas virtually always
represents a mix, and properties change constantly with depth.

7.3. DEPTHS

In diving, when gas cost is added to the equipment required, the cost to dive varies exponentially with depth. At a given depth, the choice of technique is a compromise between what can be accomplished, the quality of the product, and economy. Meaningful discussions on the subject of underwater welding require careful definition of depth, and further, a clear picture of the depth ranges in use today. They are:

(1) The splash zone, is 40 ft. (12 meters): where percentage change in properties with depth are large and there is an overriding influence of wave action. Dive times are normally unlimited.

(2) The air diving range: where the diver breathes compressed air and the depth is restricted to 165 ft. (50 meters), with time being restricted by toxicity of oxygen in the breathing gas. Welding is limited by the achievable properties and by the fire hazard, when carried out in a background gas.

(3) The nitrox range: where the oxygen percent in nitrogen is controlled to eliminate the problems of oxygen in high pressure air. As with air, the depth is limited by the toxicity of the nitrogen. Nitrogen also affects weld properties, so far restricting welds to the 115 ft. range (35 meters).

(4) The pre-mixed gas range, where background and breathing gas are supplied from reservoirs of 16% oxygen in helium. The oxygen content corresponds to the minimum metabolic requirements of the diver at the surface. Dive times and maximum depths about double that for diving with air. The limitation again is the results of the increased oxygen content with depth. The fire hazard and adverse effect of oxygen exist when used as ambient or backgroud gas.

(5) The heliox range, where the percent of oxygen is fixed with depth. Medically, this range is the kindest to divers and is the only current candidate for welds by divers deeper than 300 ft., (90 meters). This mode does not economically compete in the shallow range; and on the deep end, itself is limited to 1150 ft. (350 meters), by toxicity induced diver high pressure nervous syndrome.

(6) The Tri-mix range, with the breathing gas switched to hydrogen or other inert gas at a predetermined depth. The potential is to more than double the depth in use, but the technique is so far limited to experimental chamber dives.

7.4 WELDING METHODS

Consider the methods of underwater welding. According to D3.6, there are five basic methods currently in use. They are: (1) one atmosphere welding (2) habitat welding (3) dry chamber welding (4) dry spot welding, and (5) wet welding. More exact definitions are found in that specification.

In the same specification there are four types of underwater welds in use: Type A, B, C and 0, intended to describe the range of quality and

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properties in use today. Each defines a set of properties verified during qualification and a set of soundness requirements verified during construction. While the types are not necessarily related to a specific method, it soon becomes apparent to users that certain methods are suited to the production of certain types of underwater welds; for instance, the Type B weld is today a quality wet weld. Other types are defined with more emphasis on purpose; Type A is a structural weld, Type C is a non-structural wet weld, and Type O also meets the requirements of another designated code or specification. A significant aspect of D3.6 is that weld procedure development is performed by contracting personnel. As a result, inspection methods can be developed as a product of the Procedure Qualifications Trials.

7.5 INSPECTION PROCESSES

The common processes used for inspection of underwater welds are: Visual, Magnetic Particle, Ultrasonic, and Radiography. There are no basic changes in the processes when used underwater; however, technique and equipment changes are required to deal with the increased pressure, the seawater or gas environment, and the remote site. Equipment is commercially available and it spans a wide range of price and performance. Prior qualification of equipment and procedures for examination of welds underwater is an essential.

Acceptance criteria for defects in early underwater welds were adapted from available codes such as ASME or API. In D3.6, the acceptance criteria are tailored to the type of weld produced, and the criteria are quite liberal. This is possible because most criteria in exisiting codes are standards of workmanship and, as such, are only secondarily related to the ability of a structure to carry a load. Defect acceptance criteria in today's codes are adequate, but Non-linear Fracture Mechanics and materials technology, combined with more exact resolution for stresses, have refined the flaw accessment practice and broadened the limits of acceptability. The change is not confined to D3.6. The assessment of individual defects in existing structures offshore is being performed on a routine basis. That trend is likely to increase in the future and also increased use of other advanced methods of inspection, such as those which monitor stiffness and acoustic emission will continue.

Consider the aconomics of the situation. When a weld is inspected in a fab shop, the customer pays for the time of two technicians and equipment, which might include a film lab, UT gear, or similar. Customers often complain about the cost. When an individual inspects a weld underwater there are any number of personnel topside in a supporting role. The numbers increase with depth and complexity of the job to the point where a very expensive vessel, and 100 individuals may be standing-by, as the inspection proceeds. This economic cost of the work provides the driving force to improve task performance.

Not many years ago diving companies worked on a day rate basis. Personnel and equipment were rented, and best effort was the accepted norm. A little sandbagging to raise the profits even sometimes was tolerated. Today, the fixed price contract has changed all that. High profits were not always well spent; however, profit margins today have reduced or eliminated the budgets needed for equipment development.

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Two additional aspects of underwater weld inspection are: (1) for existing structures 80% of the time and cost can be taken up removing growth from the surface to be examined. (2) Once the structure is cleaned the lack of precise nomenclature can render the data useless.

7.6 EQUIPMENT CONSIDERATIONS

Diving, welding and inspection benefit from each advancement in equipment. Recent years have produced three phases of development. In the first, all equipment possible was located at the surface and umbilicals provided the link to the diver. Fifty or more umbilical members to do a single job was not uncommon. In the second phase, equipment used by the diver, where possible, was moved to a fixed position on the bottom or hung from the surface. Phase three, now under development, will find equipment guided to the work site from the surface, under its own power. It will attach itself, check itself out to make sure it works, and then provide a light and a place for the user to stand. When a job is completed, this same equipment will return to the surface without assistance from the diver. This generation of equipment may be the usher for remote weld inspection. On an underwater job recently, I worked with an independent diver-inspector who came to the job complete with equipment and procedures, and with the necessary diving and inspection qualifications. He signed a short term contract to provide inspection services and worked with the contractor's equipment and personnel. That individual is surely the forerunner of a true Underwater NDE Professional.

P. Watson

7.7 PREFACE

The Inspection workshop was comprised
of the Chairman, Co-Chairman and personnel
represented a range of the various
disciplines of the underwater welding and
inspection industry.

This group found that the inspection
operations are a vital and integral part
of underwater welding nd that inspection
of subsurface marine structures is often
the first operation used to determine the
need for underwater welding and to
establish planning and selection of proper
welding techniques for replacement,
modification or repair operations to
follow. Inspection is necessary to assure
the quality and soundness of the
underwater weldments.

7.8 INSPECTION

The following representative areas considered by the work group as
warranting further study. Although these areas are by no means complete, and
are not intended to represent a comprehensive coverage of the subject.

7.9 DEEP WATER INSPECTION SYSTEMS

A new report was produced by Busby Associates, Inc., under contract to
Minerals Management Service (MMS) Department of the Interior, which discusses,
in detail, systems that are currently available to assist in inspection of
structures in deep water. This report, entitled, "Undersea Inspection of
Subsea Production Systems", was published in June 1985 and it is available
from MMS.

There are three primary approaches which are used to assist in underwater
inspection. They can be classified as:

o   Human intervention
o   Remotely operated vehicles
o   Hybrid systems

There are currently two basic means of utilizing human intervention in
inspection systems. One is to place the human in contact with the water at
ambient pressures. The current maximum working depth for this approach,

depending on the type of breathing gas and diving equipment used, is approximately 1000 feet of water. The second is to place the human in a dry, one atmosphere pressure vessel for performance of necessary work which is done through the use of manipulators/tools and thrusters while visually observing the work area. The current maximum working depth for these systems, specifically submersibles, is approximately 3,000 feet of water.

Remotely operated vehicles are basically divided into two classes. Neither of these vehicles contain humans. The first class can be called tethered control vehicles. Thethered vehicles are tied to surface support ships with tethers which include control, power cables, and T.V. cables. They may or may not have thrusters but movement is controlled by operators on the surface support ship. The current maximum working depth for these vehicles is approximately 8,000 feet of water. The second class can be called untethered or autonomous vehicles. These vehicles have thrusters for movement and may be tied to the surface by a thin communication or may be pre-programmed to perform specific tasks at specific depths and locations. The current maximum working depth for these vehicles is approximately 18,000 feet. However, both classes of vehicles are limited to operations in water currents not exceeding approximately 2 knots and to operations away from dense structures. Further, autonomous vehicles are limited by their on-board power sources to approximately two hours of operating time.

Hybrid systems use a combination of the previously discussed two approaches and have some of the limitations of each.

7.9.1 Recommendation

Development of more tools to be used by and functions to be performed by remotely operated vehicles are recommended to allowing divers to perform more detailed tasks in less dangerous waters and depths. This will allow better utilization of divers at less personal risk. It will also allow divers to become highly trained technicians capable of performing more detailed tasks.

7.10 IMPETUS OR REQUIREMENTS FOR NDE OF UNDERWATER WELDING
7.10.1 Industry Experience in United States Waters

       a.   Some structural failures are not deemed to be of great significance and, in such cases, visual inspection of repairs normally is sufficient. However, magnetic particle and/or U.T. inspection is normally used for repairs to more critical elements.

       b.   The owner or operator must submit a damage report/repair procedures to appropriate regulatory bodies when structural damage is significant. Appropriate regulatory bodies are the U.S. Coast Guard for MODU's and the MMS for fixed platforms and flowlines. Pipelines to shore are regulated by the Department of Transportation. Inspection methods and acceptance standards must also be submitted and approved.

7.10.2 Industry Experience in Non-United States Waters

a. The Norwegian Petroleum Directorate treats each case individually within the limits of their general regulations and NDE inspection is approved and carried out as described for the U.S. although to a somewhat greater extent.

b. The British Department of Energy has more specific rules for inspection of underwater welding, and supplement those with the requirements of any appropriate certifying authority.

7.10.3 Recommendation

The approaches listed above are felt to be sufficient, in that they provide for reasonable and adequate inspection of welding performed in the waters of the countries mentioned. However, since inspection for welds made in other locations (e.g. individual state waters or other foreign countries) may not be required, some standard should be applied for such areas.

7.11 CLEANING OF STRUCTURES

Practical weld inspection of structures in service today is being hampered greatly as a result of the high cost associated with removing marine growth and corrosion from the surfaces to be examined.

In service inspection of structures could therefore be substantially facilitated by the continued development of an unmanned vehicle remotely operated, surface disconnected to the greatest possible extent, able to remove corrosion and marine growth from structure surfaces to allow more rapid final cleaning of surfaces to be inspected. This should be combined with added research on corrosion alternatives to prevent the black oxide from forming on structure surfaces which will facilitate in-service inspections.

7.12 GLOBAL VERSUS LOCAL INSPECTION
7.12.1 Global Inspection

Global inspection is used to determine the overall behavior or condition of a construction/structure. Typical techniques used are remote visual inspection with optical or mechanical aids to determine changes in shape (deflection), position, orientation vibration (including flexibility) monitoring and loss of product flow. Possible or less frequently applied techniques are integral acoustic emission measurements, measurement of transmission of (ultra) sound or electric currents and pressure measurements. In general, global inspection lacks proper use and interpretation of results.

7.12.2 Local Inspection

Local inspection falls into two groups:

a.   Inspection to disclose gross deterioration.

b.   Inspection to detect and characterize finer defects.

7.13 Gross Deterioration Inspection

Deteriorations being looked for are dents or other accidental damage, implosion of structural elements, missing members in offshore platforms, debris (which could cause damage), sacrificial anode condition and functioning, and coating damage. Cleaning is usually not necessary.

The dominant techniques are visual examination and electrochemical potential measurements using divers or remotely operated vehicles. Less frequently applied techniques are ultrasonic, flooded member detection, use of sonars, and the use of other optical or ultrasonic imaging systems (including image enhancement), and local vibration analysis.

7.14 FINER DEFECT INSPECTION

Inspection done usually after cleaning to reveal and describe defects, service induced cracks, as well local or general corrosion. Frequently applied techniques are close up visual examination and magnetic particle examination. Ultrasonics (including use of automated equipment) is used for fabrication or repair work. Ultrasonic and AC transmittance drop techniques and radiography are applied to a certain extent along with acoustic emission.

7.15 ACOUSTIC EMISSION

Finer defect and eddy current weld examination are upcoming inspection techniques designed for in-service inspection mainly done on a spot check basis based on a design, fabrication installation, and inspection plan or on results from gross deterioration inspection.

7.15.1 Recommendations

(1)   Global inspection should be taken more seriously and better correlation should be established between inspection results and local deterioration.

(2)   Monitoring techniques (acoustic emission, vibration analysis) should be further developed for practical application.

7.16 EQUIPMENT AND PERSONNEL QUALIFICATIONS
7.16.1 NDE Personnel Qualification

1.   Diver/technicians should be qualified to ASNT (or equivalent) standards

Printout cancelled by operator.

2.   A minimum of one diver/technician qualified to ASNT level II should be required when any NDE work is in progress.

3.   An ASNT qualification should be earned through examination by ASNT personnel rather than by the company.

4.   All diver/technicians should be qualified for the diving mode required for the depth of the inspection.

5.   Diving should be done in accordance with the established rules for the area (USCG, etc.).

6.   Diver/technician should be fluent in the specified language.

7.   Diver/technician should have a predetermined number of hours experience with the specific equipment that he/she is to use.

7.16.2 NDE Equipment Qualification

1.   Electrical equipment should utilize a ground fault interuptor service.

2.   Equipment should be designed to operate at specific depth – maximum depth to be marked on equipment.

3.   Radiographic camera or x-ray equipment should be equipped with both surface and underwater controls. Radiation meter on device (installed or available to diver).

4.   Umbilical (if required) shall be free of cover breaks, tears etc. Connectors to be designed for depth required.

5.   Equipment operated within parameters established by manufacturer.

6.   Topside portion of device shall be protected from weather (watertite case etc.).

7.17 NDE RELIABILITY AND CONFIDENCE LEVEL
7.17.1 Background

Various NDE techniques have been discussed to date for underwater inspections. But no reliability and confidence level of each inspection technique has been mentioned. It is not reasonable to assume that, after each inspection and/or repair and re-inspection if necessary, the area inspected is defect free. Two questions of interest, are: to determine, under normal service conditions, when to conduct the inspection again? Given that the sensitivity and confidence level of each inspection technique can be established, with the aid of fracture mechanics calculation, perhaps then a determination of the frequency of inspection, and selection of inspection tool can be made.

7.17.2 Current Status

1. U.K. Department of Energy has a guidance that an offshore structure should be inspected every five years and that the owners of platforms have responsibility to establish their own inspection program and report the problem if found.

2. There is no criterion for establishing an underwater inspection program.

7.17.3 Future Needs

1. To establish the sensitivity and limitation of each inspection technique.

2. To develop a criterion for establishing the priority and frequency of inspection.

3. A criterion for selecting a inspection tool based upon its sensitivity and a given inspection interval.

7.18 STANDARDS OF ACCEPTANCE

Many existing standards of acceptance, especially with respect to welding flaws, are based upon workmanship criteria, or upon indications which appear prominent in a particular type of NDE (e.g. porosity on a radiograph). These standards have proved to be adequate for most above water applications. In many cases, however, these criteria are unnecessarily severe, and where underwater welds are involved, the standards can result in extremely costly repairs to superficial or non-critical flaws.

Ideally, the acceptance or rejection of each flaw in a structure or pipeline, would be based upon the fitness-for-purpose of the weldment. Unfortunately, the state-of-the-art of fracture mechanics has not yet reached the stage where a precise judgement can be made in all instances. Nevertheless, the door should be left open for such an approach, and any code/recommended practice/etc., should retain the option for engineering critical assessment, subject to a suitable factor of safety to account for "worst case" discrepancies in measurement and calculation.

In order to refine fitness-for-purpose methodology, research is needed in four distinct areas:

1. NDE methods for determining more precisely the actual depth, size and orientation of a flaw.

2. Simple, reproducible tests to characterize the fracture toughness of welds, including heat-affected-zones.

3. Better methods for estimating stress distribution and lifetime fatigue stresses in structures and pipelines.

4. A better knowledge of the probability of detecting flaws (e.g. cracks) for assessment.

The forgoing approach will be very cost effective. As an example, during the 1970's, a single 30" pipeline tie-in in 600 feet of water in the North Sea cost on the order of $5,000,000. Costs have decreased significantly since then, but nevertheless the cost of a single, unnecessary cut-out can support a significant research effort.

7.19 NONDESTRUCTIVE EXAMINATION AND DOCUMENTATION

Present underwater nondestructive examination (NDE) techniques used rationally in evaluation of subsurface structures include the following:

1. Visual Testing (VT): Performed by a diver/inspector, with or without visual aids, and documented by photography or video tape. Deep examination can be performed by manned submersibles or by remotely deployed vehicles but are limited by accessibility of individual joints or components.

2. Magnetic Particle Inspection (MPI): Nearly always performed by a diver/inspector and not always documented, depending upon the results of the examination. Interpretation of indications is sometimes difficult.

3. Radiographic testing (RT): Nearly always performed by a diver/inspector and documentation is inherent in the technique.

4. Ultrasonic Testing (UT): Nearly always performed by a diver/inspector. Some UT examinations are monitored at the surface by duplicate instrumentation and some are not monitored. A video records can be made of the CRT display but correlation with transducer position, and skew must be taken into account. A high degree of skill for both the transducer manipulation (diver) and surface evaluation (NDE technician) is necessary.

The above four techniques all depend on a clean weld joint and surrounding base metal. There are however newly developed techniques that could be applicable to subsurface examinations. Eddy current technology has been developed that allows examination of weld and HAZ for surface flaws. Acoustic Emission Testing (AE) is a passive system that is capable of full time (or part time) monitoring of the structure but has limitations on pinpointing the problem area or how severe the problem might be. Monitoring of the natural frequency of a structure can determine if major failures have occurred.

Data acquisition systems have been developed for above surface examinations, particularly for UT and AE which allow continuous monitoring of the examination, recording of the critical parameters of the examination, and provision of a permanent record. Subsequent analysis of this data can then be made top side, with or without the aid of computers.

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7.20 CONTRACTING FOR DIVING INSPECTIONS

There are two basic kinds of diving inspections carried out by contractors:

1. Routine inspection prior to repairs, or to determine the need for repairs of marine structures and vessels.

2. Post work inspection of repair or construction operations.

Owners should consider contracting for inspection diving services on a time and materials (T&M) basis versus contracting lump sum. Certainly diving contractors can perform mobilization and demobilization on a lump sum basis. But owners will be better assured of an adequate and thorough inspection if the work is performed on a T&M basis.

If there is any significant underwater work to be done, that cannot be verified by simple TV monitoring at the surface, then the owner should employ inspection divers, separate from the working dive crew to verify the adequacy of the work with an unbiased inspection.

7.21 VISUAL INSPECTION

Visual inspection is a commonly used technique can provide a high confidence level. It requires a highly skilled individual.

7.21.1 Current Practice

Clean manually, then observe the following:
    Weld surface/joints
    Buckles and other obvious damage.
    Discoloration/coating loss/obvious corrosion.

Lighting:
    White spot lights, lights usually with lines to surface
    (Batteries limit time/power/movement)

Water Clarity:
    In the absence of arctic temperature hot water units, time limit is roughly 20 min. @ 37°F for feeling damage in dirty water (when water clarity is too poor for visual capabilities).

Training:
    Full time engineer and part time divers are required.
    Occasionally run low on engineer/diver personnel. Usually 6-7 people are needed on inspection team.
    Mix of civil and mechanical engineers needed.

Cost of inspection vs rewelding or failure:
    Inspecting large structures in emergency situations is very difficult and costly. The stressed points should be inspected every year.

Remote Visual:
>   Video - acceptable for major damage but difficult to see too many
>   minor defects, limited to cleaned areas.

35mm:
>   Good for record but limited by water clarity. Before arrival,
>   engineers can get an idea of damage, but photography/development
>   quality may be poor. Developing lag time may require another dive.
>   Limited amount of exposure distorts size of subject. Listing
>   location of photos can be lengthly and confusing especially in bad
>   water conditions.

Pre Inspection Plan:
>   1.   Repair or inspect only?
>   2.   Contingency for bad vision?
>   3.   Divers tie-off or go off bank or structure. Some difficult
>   jobs have platform or barge.

Safety
>   Limit dives on air to safe diving depths
>   Entry to structures limited.
>   Electrical interference can be severe around power lines
>   Great depth or temperature extremes severely limit time.

7.21.2 Needs

Inspection technology has the following needs:
>   Environmentally acceptable.
>   Public acceptable.
>   Remote system "Borescope" TV - small size.
>   Recording ability without interference.
>   Repairs could still be conventional.

All inspection systems eventually come to some type of visual
inspection. It is very important that the person be enough of an engineer,
welder, and NDE technician to make a balanced decision as to the impact of the
defects and abilities of the NDE system.

7.22 NEW DATA ACQUISITION AND PROCESSING SYSTEM

Adapt data acquisition and processing systems currently being utilized in
new above water NDE R&D efforts to existing underwater NDE methods. The
following should be considered:

o   Utilize intelligent processors to filter out background or stray
      readings.

o   Integrate the data to provide enhanced defect signal.

o   Provide confidence level based on strength of indication or other
      factors.

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o   Take the interpretation of the operator "out of the loop".

o   Provide a surface mapping overlay of where the defects are located.

7.23 RECOMMENDATIONS

Present state of the art surface technology in automation of inspection systems, development and application of data acquisition, signal processing, inhancement techniques should be studied for application to underwater examination. Development of such systems for application to present and future examinations could more dependably provide necessary information to determine fitness-for-service of a given structure.

VIII.A. ADVANCED TECHNOLOGY - WHITE PAPER

"Some Ideas About the Future Developments of Underwater Welding Technologies"

K. Masubuchi

8.1 INTRODUCTION AND GENERAL COMMENTS

As many of you already know, underwater welding has been performed since the 1900's. However, underwater welding was done or studied by only a small number of people until about 25 years ago. Activities on underwater welding started to increase significantly around 1960, primarily to meet the new demands for construction and repair of offshore oil- drilling rigs and pipelines. In 1960, there were 62 offshore oil-drilling rigs in the world but the number has increased to more than 500 today. Underwater welding technologies have improved significantly since the 1960's. For example, hyperbaric dry habitat welding, which is widely used for underwater repair and construction of offshore pipelines and other structures, originates from the 1954 patent by Osborn; but its major development occurred in the 1960's.

It is interesting to note that most of the development of underwater welding during the last 20 years was done by people who actually performed the underwater welding jobs. The agencies and companies that sponsored these research and development activities were interested mainly in having certain welding jobs done, rather than improving the understanding of the underwater welding phenomena. There have been comparatively few scientific papers on underwater welding. There is nothing wrong with this practical approach; perhaps the practical approach is the quickest way to accomplish what needs to be done. The problem is that without improving the basic understanding of what actually goes on during underwater welding it becomes increasingly difficult to further advance the present technology. In my opinion, the present state of underwater welding technology has been developed as far as is possible, without a significant improvement in the basic knowledge of underwater welding. I strongly believe that to efficiently advance the present underwater welding technology, we must improve our basic knowledge of underwater welding phenomena. The fundamental reason for holding this two-day international workshop is (a) to take stock of the present state-of-the-art of underwater welding and (b) to develop plans for future actions necessary to further advance the current technology. I would like to stress the need for fundamental research on underwater welding.

Before discussing subjects related to advanced technology, I would like to briefly point out two subjects which I think very important. One is the need for developing a reliable and impartial data base on the properties of underwater welds. Although many companies have developed underwater welding

technologies, much of the data has been keep proprietary. Therefore, people who are interested in underwater welding jobs, do not have access to reliable existing data. It is extremely important to develop a data base accessible to the public. I hope that this subject is discussed in another session, perhaps in the session on "Shallow Underwater Welding".

The second subject is the effect of hydrogen in underwater welding. We all know that hydrogen causes serious problems in welding. In fact, in welding high strength steels on land, extreme care must be taken to limit the level of hydrogen in order to prevent weld cracking. We know that very large amounts of hydrogen exist in the welding environment, especially under "wet" conditions. Even in hyperbaric dry welding, I suspect that the environment can be rather humid, or the hydrogen content could be considerably higher than that expected when dry welding on land. The problem is extremely important in welding high-strength steels, especially under increased pressures. I expect that this subject will be covered by Dr. Hans Hoffmeister, Chairman of the session on "Deep Underwater Welding".

When we talk about advanced technologies which can be applied to underwater welding, we probably should cover many subjects. However, since I have only a short time for my presentation, I would like to discuss two subjects which I think important:

1.   Automation and robotization in underwater welding

2.   Use of advanced, improved steels for reducing cracking and material degradation due to underwater welding.

8.2   AUTOMATION AND ROBOTIZATION IN UNDERWATER WELDING

At present, almost all underwater welding jobs actually performed in both dry and wet conditions are performed manually. In recent years, however, some research efforts have been made to introduce automation and robotization in underwater welding. I believe that these efforts will increase in the future. In fact, automation is essential for developing underwater welding technologies for deep sea applications. Discussions here cover the following subjects:

1.   Needs and difficulties related to automation in underwater welding.

2.   Uses of robots in welding fabrication.

3.   Research and Development efforts on automation and robotization in underwater welding

4.   Summary and future possibilities.

8.2.1.   Needs and Difficulties Related to Automation in Underwater Welding

The need for automation in underwater welding is indeed very great for the following reasons:

(1) Any underwater welding job is very expensive and it always involves some operations that are hazardous to welders/divers. Even in shallow water, poor visibility and a lack of body stability as well as extreme cold may hamper a welder/diver performing wet welding or welding in a mini-habitat. As the depth increases, even harsher constraints are imposed. Unless saturation diving techniques are employed, allowable diver working time decreases drastically as depth increases. Therefore, any mechanical assistance to welders/divers in (a) improving the weld quality and/or (b) increasing operational capability and safety, is very useful. Beyond a certain depth, even saturation diving techniques cannot be used; then, submersibles or remotely controlled work vehicles must be used. The only possible means of performing cutting and welding operations in deep sea are through complete mechanization and automation.

(2) Although most actual offshore oil production comes from depth less than 400 feet, exploratory drilling has been conducted in water depths greater than 3,000 feet. As the development of offshore oil fields expands, drilling and production will go into deeper and deeper waters. There is a strong demand for developing cutting and joining capabilities at greater depths. The Committee on Establishing and Maintaining Underwater Arcs and Flames, of the National Research Council, has recently studied the technical feasibilities of using metal arcs and gas flames for cutting operations in waters up to 6,000 feet deep or even more.

The are basically two factors which limit the use of certain joining processes for deep-sea applications (1): 1. Diving systems limitations and costs. 2. Depth-related technical problems.

Within the scope of this paper, a manned submersible is considered to be any undersea vehicle capable of transporting a man or men at a constant pressure, and capable of performing some manipulative work underwater. Submersibles of a variety of design and capabilities (as deep as 20,000 feet) have been built and used for various purposes. The limitations, as they affect joining techniques, are not depth-related but determined by the manipulative devices of the submersibles. The vehicle may be remotely operated. Several remotely operated maintenance systems intended to perform predetermined work on undersea structures have been developed. Today there are underwater vehicles capable of performing various jobs including exploration of minerals, under-ice surveys, inspection of underwater structures, deep-sea photographic surveys, and military surveillance. Manipulators currently available can perform simple tasks, including picking up sunken objects, grabbing subjects, taking photographs, and cleaning surfaces. However, there is no submersible capable of performing underwater welding tasks, to the best knowledge of the author. Basic research on underwater welding and cutting by remote manipulation techniques is currently being conducted at M.I.T. (2).

8.2.1.1 Diving System Limitations and Costs

Diving systems of interest may be divided into these two groups:

a.   Systems with a direct man-work interface:
            1.   Conventional diving.
            2.   Saturation diving.
            3.   Ambient pressure diving.

    b.   Systems with a remote man-work interface:
            4.   Manned submersibles.
            5.   Remotely operated work vehicles.

The systems in the first group have a direct man-work interface in which the diver/operator gets hands on the work. The systems in the second group have a remotely controlled interface in the form of manipulators, television cameras and other devices.

Surface diving is suited for short-time missions in shallow waters. Decompression is required after only a few minutes when working in depths of less than 100 feet. When air is used to breathe, the safe depth limit is about 200 feet; with a helium-oxygen mixture it is less than 400 feet. Using saturation diving techniques, divers can keep in a living chamber beyond 1,000 feet and transported to a job site for work shift periods of approximately 8 hours.

Several commercial diving companies that serve offshore oil industry use underwater welding chambers to obtain a dry environment at an ambient pressure. A welding chamber is attached to the structure on which welding is to be done, and the water in the chamber is displaced by pressurized gas. Then divers enter the chamber from the bottom. This hyperbaric dry chamber welding is widely used for the construction and repair of undersea pipelines and other structures. A submerged chamber maintaining a constant pressure of one atmosphere is another solution for underwater welding. The mechanisms of welding in this case are essentially the same as those in ordinary welding in air on land. The one-atmospheric welding can be performed at any depth as long as a diving system is developed. However, this technique is very expensive, primarily due to the cost of construction and deployment of the pressure vessel involved; therefore, this technique is seldom used.

8.2.1.2   Depth-Related Technical Problems

As the operating depth increases, the effects of pressure on the joining processes become of greater importance. Pressure effects on the arc are common to all arc welding processes. As the depth and hydrostatic pressure increase, the arc is increasingly constricted resulting in increased current density. Therefore, higher voltage is required to maintain a constant arc length. An increased pressure also affects the behavior of the shielding gas, and higher flow rates are required as the density of the gas increases. Other joining processes also have some problems caused by increased operating depths. I believe that these subjects will be discussed in the session on "Deep Underwater Welding". A forthcoming final report of the Committee on Establishing and Maintaining Underwater Arcs and Flames should contain important technical information on depth-related technical problems, although the emphasis of the report will be on cutting rather than welding.

Some underwater joining processes require large amounts of electric power, and some of the processes require shielding gases as well. In relatively shallow waters, these items can be provided by cables and hoses from the surface. These problems become more complicated as the depth increases. Different sets of problems occur, depending upon the diving system used, resulting in different solutions. For example, for deep-sea joining using remote manipulation techniques, completely automated and integrated systems using such joining processes as explosive joining, friction welding, and stud welding, may be more suited than systems using shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), and gas metal arc welding (GMAW) processes.

8.2.2 Uses of Robots in Welding Fabrication

The uses of welding robots are rapidly growing in major industrial nations. Figure 1 shows the infusion of industrial robots each year since 1964 in the Federal Republic of Germany, Japan, Sweden, the United Kingdom and the United States (3). Also indicated by arrows are the years when robots in Japan did not occur until late; however, the infusion of robots in Japan has been strong and consistent. Sweden had exhibited strong infusion in the 1970's with a recent slowdown, while West Germany has shown a somewhat later but very strong and continuing growth in its robot population.

A significant percentage of industrial robots are welding robots, although these numbers are not shown in Figure 1. Many of the first welding robots were mainly spot welding robots. Since arc welding robots require more complex and accurate controls than spot welding robots, it took more time to develop arc welding robots. However, the use of arc welding robots has increased almost explosively since 1980.

Most industrial robots used thus far may be called first generation robots, which primarily use "teaching playback" control systems. Since they lack adaptabilities in real structures, their fields of application are limited. These first generation robots are suited for applications in which the relative position between the robot and the workpiece is kept unchanged, and a robot is required to repeat faithfully the motion path taught by a human. On the other hand, the first generation robots are not suited (or have not been used extensively) in applications with these characteristics:

1. A few repetitions of the work are required (small lot-size production)

2. Physical movements of a robot are required, or the robot must move to different locations to perform the work

3. When sensing (either by vision or touching) and judgement are required.

These requirements are important in the fabrication of various structures including ships, offshore structures, airplanes, and heavy machinery.
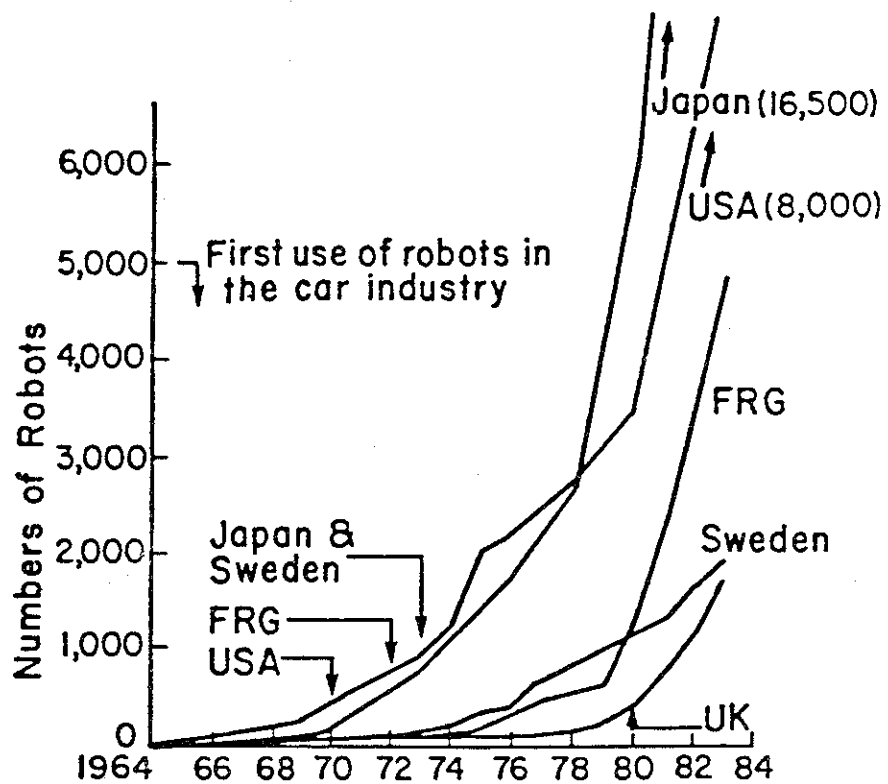
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Figure 1. Diffusion of Industrial Robots.

Very recently, some development efforts have been made in the area of simple vision systems, such as those using laser light beam and television cameras. This indicated the development of what may be called the second generation robots. The second generation robots are capable of performing certain adaptive controls by use of simple vision and force sensors. For example, in arc welding, when the points of arc initiation and finish are taught, the welding machine can follow actual joints to be welded. With the development of second generation robots, uses for welding robots in such industries as shipbuilding and offshore construction are rapidly increasing.

As can be seen from these developments, it is safe to say that uses of robots in underwater welding will be accomplished and increased in the future. The unique characteristics of underwater welding fabrication using robots are as follows:

1. Technical difficulties. There are a number of difficult technical problems which must be solved. For example, the system must work underwater requiring some critical components to be watertight. Sensing systems also must work underwater.

2. High cost ceilings. Since most underwater jobs are very expensive, the cost of construction and operation of a system can be quite high, so long as it can perform the intended jobs satisfactorily. In fact, with the proper use of robots, many jobs which cannot be performed at present may become possible. Then the cost is not a critical limiting factor.

3. Limited market size. The market size for most underwater welding jobs will be smaller than those for similar jobs on land.

8.2.3 Research and Development Efforts on Automation and Robotization in Underwater Welding

At present, it is quite possible that researchers at a number of laboratories in various countries are engaged in research programs with objectives of developing unmanned systems for underwater welding. In preparing this paper I did not have time to perform an extensive survey of literature on automation and robotization in underwater welding. Perhaps some people who are attending this workshop already know of many new developments on this subject. Described below are some of the works with which I am familiar.

8.2.3.1 Research Efforts at M.I.T.

Research at M.I.T. has been working on the development of unmanned underwater welding systems for several years. APPENDIX I is a paper entitled "Development of Fully Automated and Integrated 'Instamatic' Welding Systems for Marine Applications" presented at the 1983 Offshore Technology Conference. This paper describes results of a two-year program (from July 1980 through June 1982), the objective of which was to develop fully automated and integrated welding systems. These systems package many actions involved in welding so that certain prescribed welding jobs can be performed by a

person with no welding skill. They have been nicknamed "Instamatic" welding systems, since they are similar to the easy-to-operate cameras. Following a general discussion on the development of the concept of the "Instamatic" welding systems, discussions are given on the two types of systems which have been built and tested: underwater stud welding systems, and those using arc welding processes.

Since July 1982, the M.I.T. researchers have been working on a research program entitled "Underwater Welding and Cutting by Remote Manipulation Techniques" (as stated on the first page of APPENDIX I). Reference (2) describes the results obtained in the current program. A remotely operated stud welding gun has been developed, and it has been proven to work successfully in a dry atmosphere up to a pressure level of 250 psig, which is equivalent to the water depth of 580 feet. This pressure is the maximum pressure that can be safely tested using the current facility available at M.I.T., not the maximum pressure under which the stud welding system operates successfully. Regarding stud welding under wet conditions, acceptable welds have been made in dry conditions until the moment of the arc initiation. Efforts continue to see if the stud welding gun can be successfully operated when it is mounted on a remote manipulator attached to a remotely operated vehicle (ROV).

8.2.3.2. Research and Development Efforts at Various Laboratories and Companies

At the International Conference on Underwater Welding held in June 1983 in Trondheim, Norway, many papers were presented covering a wide range of subjects related to underwater welding. For example, Reference (1) was presented at the Conference. Some of the papers presented cover subjects related to the automation and mechanization of underwater welding.

1. van der Torre and Spikes of the Netherlands discussed remote-controlled underwater welding in dry condition.

2. Knagenhjelm of Norway discussed the mechanization/automation of hyperbaric welding using gas tungsten arc (GTA) welding.

3. Asnis and Savich of U.S.S.R. discussed the mechanized wet underwater welding technique developed at the Paton Electric Welding Institute. A special self-shielding flux-cored wire was developed.

4. Savich and Ignatushenko of U.S.S.R. have developed the technology of underwater wet welding using flux-cored wires.

Also a recent report by Lyons and Middleton of U.K. discusses an orbital GTA system, or OTTO system, for girth welding pipes and pressure vessels under dry hyperbaric conditions (4).

8.2.4 Summary of Future Possibilities

Despite the fact that welding automation and the uses of robots have been rapidly spreading in welding fabrication on land, almost all current underwater welding operations are performed manually by divers/welders. Even in shallow waters, divers can work only a short time each day; therefore, the cost of underwater welding operation is very high. As the depth increases, welding becomes increasingly costly and hazardous. Further, as the operational depth increases, a diver/welder experiences considerable reduction in physical dexterity and ease of vision. I strongly believe that it is possible to introduce automation in underwater welding, to (a) improve weld quality and (b) reduce fabrication cost. In fact, mechanization is essential to the development of future underwater welding technologies, especially for deep-sea applications.

One possible method of introducing automation in underwater welding is to replace human welders working in a dry chamber with welding machines or robots. Some efforts have been already made along this line, and further research and development efforts will probably be made in the near future. In other words, this is the area where immediate practical applications are likely to occur. However, this would not result in significant cost reduction, because

1. A large chamber is still needed to house divers and the welding equipment, and

2. We still need human divers for transporting the necessary equipment into the chamber, attaching it to the joint, and activating the welding machine. A far more significant cost reduction could be achieved if one could develop a "packaged" system which can be operated underwater without human presence inside the system. A unique characteristic of welding fabrication is that it involves a series of subtasks including cutting pieces, parts assembly, welding and inspection. In order to develop truly useful "packaged" systems, it is important to integrate at least some of these key subtasks.

On the basis of the current technology, it would be extremely difficult to develop a packaged arc welding system which can be remotely operated underwater, since arc welding involves complex manipulations of the welding torch. However, M.I.T. researchers believe that it is technically possible to develop integrated stud welding systems which can be remotely manipulated underwater. These systems may be mounted on a manipulator attached to an undersea vehicle, manned or remotely operated.

In order to develop the necessary joining technologies to operate in very deep sea water where human divers cannot work, we must develop integrated and automated systems. It is likely that these system would employ joining processes other than arc welding processes, such as friction welding and explosive welding. Further studies are needed on this subject.

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8.3 USE OF ADVANCED, IMPROVED STEELS FOR REDUCING CRACKING AND MATERIAL DEGRADATION DUE TO UNDERWATER WELDING

Underwater welds, especially those made under wet conditions, have fundamental metallurgical problems as follows:

1. Due to rapid cooling during underwater welding, the heat-affected zone and the weld metal tend to have high hardnesses and rather poor fracture toughness.

2. Due to the existence of a large amount of hydrogen in the welding environment, a weld tends to have more cracks. These problems become more serious in welding higher strength steels. I believe that the seriousness of these problems can be reduced considerably by use of more advanced, improved steels.

A number of steel companies in Japan, the U.S.A., and Europe have recently developed high-strength steels which are characterized by (a) markedly reduced carbon contents, (b) relatively high amounts of alloying elements, and (c) the application of precisely controlled rolling processes. These steels are often called thermo-mechanical control process (TMCP) steels (5). Compared to conventional steels with comparable strength levels, TMCP steels have superior weldability qualities including:

a. Lower hardness of the heat-affected zone (HAZ).

b. Lower crack sensitivities.

c. Increased resistance against reduction of fracture toughness of HAZ.

Consequently, some TMCP steels can be successfully welded in air on land with no preheat, while conventional steels with equivalent strengths must be preheated to prevent weld cracking. Also, some TMCP steels may be welded using processes with high heat input while maintaining sufficient fracture toughness in HAZ.

The U.S. Navy is taking a similar approach. The Navy is interested in replacing conventional HY steels such as HY-80 and HY-100 steels, with newly developed high strength low alloy (HSLA) steels such as ASTM A710 steel. Compared to conventional steels, HSLA steels have markedly lower carbon contents.

I believe that these newly developed steels including TMCP steels and HSLA steels are more suited to underwater welding than conventional steels with comparible strength levels. More studies are needed to evaluate the extent of (a) improvements in the properties of welds and (b) reduction in fabrication costs when offshore structures are fabricated with these new steels instead of conventional steels. The studies should cover both initial construction (perhaps in air on land) and underwater repair during service.

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VIII.B. ADVANCED TECHNOLOGY — SESSION REPORT

A. Pollack

The advanced technology session discussed the present level of technology and suggested areas that would be improved by applying state-of-the-art surface technology to underwater situations. The group listed possible innovative concepts without ranking their feasibilities. Future technology advances will necessarily influence the application of these concepts.

8.5 MATERIALS

There is a need for a better under-standing of materials used in existing structures and improved materials for future construction. Both types of materials need to be considered for application in a wide range of ocean environments (gulf to artic). The following key topics are included:

8.5.1 Base Metal-Steel

o Alloying
     Weldability
     Formability
     Corrosion
     Carbon Equivalent
     Mechanical Properties

o Processing
     Microalloying
     AOD
     Continuous Casting

8.5.2 Consumables

o Hydrogen
     - diffusible
     - weld metal
     - electrode moisture
     - measurement

o Composition

o Improve Evaluation Techniques
     - hyperbaric
     - wet welding
     - develop standards

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8.6 INSPECTION

It is recognized by the Advanced Technology group that the Inspection session will cover this topic in depth. Therefore, we confined our list to topics related to advanced technology. In the following list we considered these aspects of inspection including preparation, inspection techniques, and characterization of flaw sizes.

8.6.1 Pre-Cleaning Techniques

8.6.2 Coatins to Reduce Biofouling and Corrosion

- process of application
- coating materials
    - abrasive cleaning
    - fluid cleaning
    - thermal cleaning
    - laser cleaning

8.6.3 Techniques

- Eddy current
- EMAT (electromagnetic acoustic tranducers)
- AE (Barkhausen noise)
- Ultrasonics (conventional UT improvement)
- Signal Processing: high speed transforms
                       synthetic apperature
                       expert systems
                       seismic techniques
- Radioactive tracers

8.6.4 Flaw Sizing

- improve measurements of flaw depth & length
- permanent inspection records
- fitness-for-service

8.7 WELDING PROCESSES

The shielded metal arc welding and gas tungsten arc welding processes are commonly used under water at present. Many other welding processes have the potential to be used; however, equipment and techniques have not been developed for underwater use. Following is a list of the subject areas which need to be addressed in order to offer improved quality and productivity of currently used welding processes to allow the use of new processes for underwater application.

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8.7.1 Preparation (higher productivity systems)

- water hydraulic equipment
- high velocity water jet (cutting jets)
- lasers
- plasma cutting
- carbon arc gouging

8.7.2 Processes (research into specific modification for hyperbaric conditions)

- friction welding
- plasma welding
- laser welding
- high frequency; low current
- flash butt stud welding
- hot wire TIG

8.7.3 Gases

- shielding gases that reduce hydrogen in weld deposit (i.e. stargon, gas, or other gase mixes (Ar, CO_2, O_2) (Ar, He, CO_2, O_2).
- improved arc stability

8.7.4 Power Supplies

- pulsing
- square wave
- high frequency
- AC/DC combination (multi-arc)
- miniaturization
- slope control (new for underwater)
- wire feed

8.8 ERGONOMICS

We discussed and listed technological improvements that would facilitate safety and efficiency of a diver/welder/inspector.

8.8.1 Safety and Health
breathing mixtures
electrical hazards
arc rays hazard
tyoxicity of gases

8.8.2 Habitat Improvement
- better filtration
- comfort (efficiency, productivity)
- accessibility

8.8.3 Worksite Improvement
- platform
- vehicle
- visibility
- portability

8.9 AUTOMATION
As operational depth increases, welding becomes increasingly costly and hazardous. Automation is essential to the development of future underwater technologies.

8.9.1 Welding/Inspection Sensors
image analysis
acoustic sensing
visual
electromagnetic
x-ray imaging
touch sensors
voltage sensors
visual
seam tracking
acoustic emission
pressure sensing technology

8.9.2 Intelligent Systems

- feedback algorithms
- artificial intelligence

8.9.3 Computers

- microprocessing
- feedback
- software
- environmental effects
- information management systems

8.9.4 Robotics

- non-fixed-reference system
- telepresence
- motion sensors
- water hydraulics
- supervisor/slave systems
- miniaturization
- multi-purpose robots vs single purpose
- packaging/batching

8.9.5 Vehicles

- unmanned
- autonomous (unteathered)
- propulsion/guidance
- multi purpose vehicles

8.10 STRUCTURAL DESIGN

Improved structural design could reduce life-cycle cost (initial and maintenance costs) by consideration of topics in the following list:

- repair procedures
- restraint
- stress levels
- design for inspectability
- materials

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X. Memorial Resolution

To nearly everyone in the world involved in underwater welding, the name Professor Nils Christensen is recognized. Nils contributed not only his special talents as researcher and metallurgist, but also those of teacher and, most important, as a caring human being to the field of underwater welding. Professor Christensen was preparing to leave his beloved Norway to attend this workshop when he was suddenly striken by a heart attack. His white paper on "Deep Underwater Welding" was presented by Professor Hans Hoffmeister. Nils will always be remembered by those of us who knew him.

On the following page is a memorial resolution by the workshop participants.

MEMORIAL RESOLUTION

for
Professor Nils Christensen

13th day of November, 1985

WHEREAS Professor Nils Christensen devoted much of his life to the study of
welding metallurgy, and to dedicated scientific studies of welding; and,

WHEREAS Professor Nils Christensen was a model scholarly professor and gave
generously of himself to educate young engineers and scientists; and,

WHEREAS Nils was a valued friend and collegue of welding researchers and
engineers throughout the world; and,

WHEREAS Dr. Christensen's contributions to all aspects of welding science will
stand as his living memorial.

BE IT HEREBY RESOLVED THAT:

THE participants of this International Workshop in Quality of Underwater
Welding of Marine Structures do honor Professor Christensen and give him our
utmost respect for his accomplishments; and,

THIS resolution be included in the proceedings of the workshop; and,

A copy of this resolution be sent to his wife.